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TRADEOFF ANALYSIS MODEL FOR ARSENAL SHIP SURVIVABILITY AND SUSTAINABILITY

by

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September, 1996

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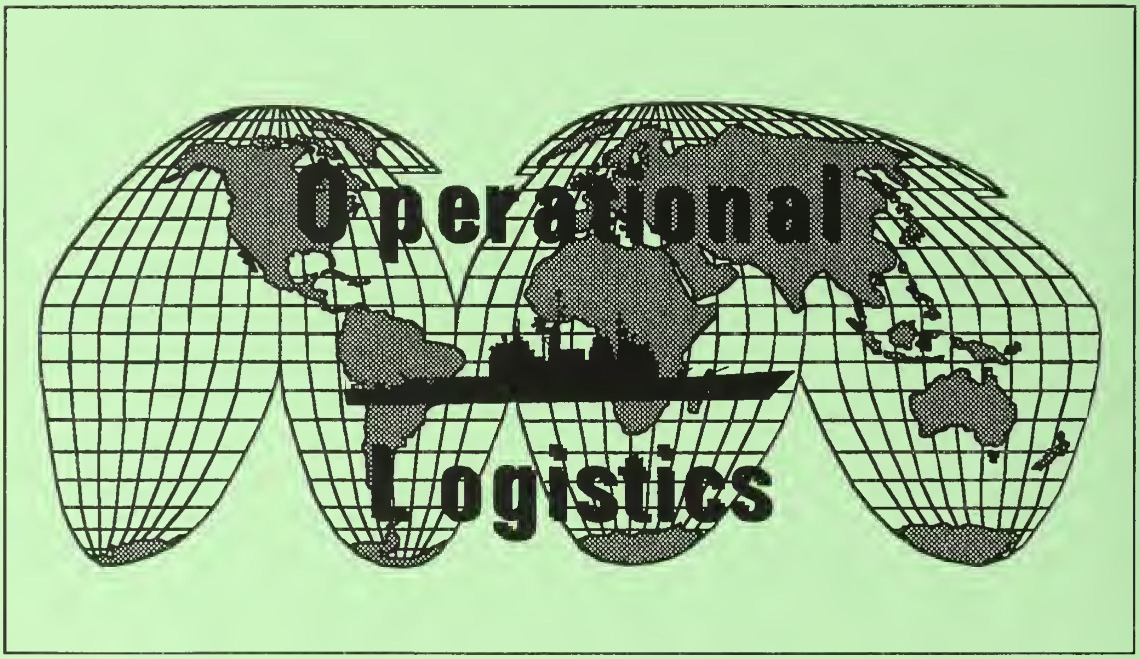
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TRADEOFF ANALYSIS MODEL FOR ARSENAL SHIP SURVIVABILITY AND SUSTAINABILITY

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ABSTRACT

The arsenal ship program is unique and requires examining the possible features of a paradigm shift in ship design. This thesis presents a user-friendly model with which a decision maker can perform tradeoff analyses between adding specific systems and technologies to the arsenal ship or adding the escort services of combatant ships. The goal of the model is to produce configuration alternatives with high arsenal ship survivability subject to a budget constraint. The model also examines operational logistics by predicting the sustainability of forces with specified arsenal ship configurations. As some inputs are necessarily speculative at this stage, the model is formatted parametrically to facilitate easy updating. A balanced arsenal ship design incorporating point defense, stealth, and hardening is the most attractive choice for littoral operations when life cycle costs are considered. The naval component must also be balanced, reinforcing the notion that stealth and staying power are important in an arsenal ship task force containing DDG-51s and SC-21s.

DISCLAIMER

This thesis contains a computer model which incorporates spread sheets, macros, Turbo Pascal source code, and executable files. While the authors have made every possible attempt to validate input data and exercise the model for all conditions, the computer model has not been validated by an independent source. The user is cautioned that some data included is perishible as costs will change. Additionally, the data incorporated in the model is unclassified; classified data may be required for the best results.

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EXECUTIVE SUMMARY

The development of an arsenal ship reaffirms the Navy's resolve to meet changing post-Cold War threats. *Forward . . . From the Sea* outlines the Navy's response for the current world order. Emphasis is on projecting power from littoral regions with naval expeditionary forces to support joint operations. In the littoral, the ship has little time to defend against advanced cruise missiles fired from land.

In designing the ship, a determination must be made on what configuration (of passive systems, active systems, and protection provided by other warships) will give the most survivability for a given price. The unique mission of the arsenal ship and the new contracting procedures of the arsenal ship program require that we examine the possibility of a paradigm shift in ship design. The ship will carry minimal active self-defense systems, so studies involving the incorporation of stealth and hardening design features (such as selective armoring) are warranted.

The Arsenal Ship Tradeoff Analysis Model consists of a spreadsheet interface for data input, result output, and Pascal program execution. Since by definition the design alternatives are speculative at this stage, the model is formatted parametrically to facilitate easy updating. Because the procurement, operating, and support costs of an arsenal ship are as yet unknown, we consider the incremental life cycle costs of adding systems over the base ship in our study. A baseline ship is an arsenal ship without any defensive systems. We believe that we can more accurately estimate these incremental costs than the cost of a conceptually new baseline ship.

The Arsenal Ship Tradeoff Analysis Survivability Sub-model is designed to track configurations, costs, and survivability. Our objective is to present a user-friendly model with which a decision maker can perform tradeoff analyses between adding specific systems and technologies to the arsenal ship and adding the protective services of other warships. The Survivability sub-model produces configuration alternatives with high arsenal ship survivability subject to a budget constraint. The model allows us to gain

insight into and draw conclusions about the value of hardening and stealth features for naval ship designs in general.

For a wide range of circumstances and measures of effectiveness, the analysis shows that building survivability into the arsenal ship is almost always preferred to assigning escorts, even when only a small fraction (18.6%) of the surface combatant's life cycle cost is charged against the escort role. Our recommendation for arsenal ship survivability features is to incorporate stealth, point self-defense systems, and hardening into the design.

Stealth characteristics and hard kill systems are, by the analysis, the features appearing in preferred designs most often. Sensitivity analysis strongly supports a moderate investment in stealth.

Even though hard kill systems were more commonly seen in the analytically preferred results than soft kill systems, we believe soft kill systems are essential for littoral operations. First, soft kill is synergistic with stealth, and the effectiveness of soft kill is amplified. Second, soft kill measures have been highly effective in actual combat, but hard kill systems remain largely unproven Operating in littoral waters with current rules of engagement (weapons not free) makes the arsenal ship vulnerable to initial and sudden attacks without ample time to respond with hard kill.

Our model shows that when surprise attacks occur, hardening is a very attractive feature of ship design. The additional staying power to remain mission capable after at least one hit will help ensure that the arsenal ship's 500-plus missiles are not rendered useless by a lucky or cheap shot.

We have gone to some pains to show that stealth, ship hardening, and defensive short range, hard and soft kill systems are complementary. For example, stealth adds nothing when the arsenal ship is firing a large missile volley, radiating, subject to air attack with bombs, surface gunfire attack, or a submarine launched torpedo attack. But, hardening retains its effectiveness in all these circumstances.

Our overall conclusion is that stealth, ship hardening, and some set of modern point defense (hard and soft) are, in view of their modest cost in construction and

operating personnel, well worth the modest cost on the margin because the arsenal ship's concept of operation requires that it be exposed to major attack.

Operational logistics is examined by exploring the sustainability of different naval component forces in the Sustainability Sub-Model. The arsenal ship program would make little sense if the ship could not improve the naval component's time on station. A highly survivable ship contributes to a force's sustainability. Sustainability is not only measured in days on station, but also in terms of incoming missiles that can be countered, since the solution is scenario-dependent. This key aspect of logistical robustness has not received the attention it deserves.

The arsenal ship alleviates the requirement to frequently cycle surface combatants with fewer VLS cells from the scene of action off station to a replenishment site and back again into the action. By its presence, the arsenal ship will sustain other surface combatants on station. It can remain on station longer than any other ship for a given missile delivery rate, but when its weapons are expended the reload problem will take it off station for a considerable amount of time.

A balanced design will seek to maximize the arsenal ship's net delivered firepower over the combat life of the ship. Incorporating *all features* listed is, according to the analysis, tantamount to over-designing arsenal ship survival features, when its survival *with those features* is compared to the survival of the accompanying present-day surface combatants. Since the DDG-51 and CG-47 cost roughly the same to procure as an arsenal ship-plus-missile load-out, and they will be less survivable, this may appear out of balance. However, in the future as more Arleigh Burke destroyers and SC-21 type warships enter the fleet, matching stealth and superior hardness will provide operational balance.

I. INTRODUCTION

A. BACKGROUND

On May 23, 1996, the Defense Advanced Research Projects Agency (DARPA) released the Arsenal Ship Program Solicitation. The arsenal ship will be designed commercially and benefit from streamlined contracting procedures with early contractor involvement. The program is managed by the Arsenal Ship Joint Program Office, under the cognizance of DARPA, and will follow a five stage process. In July, five industry teams were awarded Phase One contracts to develop preliminary designs. Phase One will last for six months, after which the top two teams will be awarded Phase Two (one year) contracts to develop more detailed, functional designs. In Phase Three, one team will be selected to construct a prototype or demonstrator. Phases Four and Five constitute operational evaluation and production [Refs. 1 and 2].

1. Requirements

The Naval Postgraduate School's Total Ship System Engineering (TSSE) team has been tasked to develop an arsenal ship design which might assist in exploring options being considered by industry teams. Before designing the ship, a determination must be made on what configuration (of passive systems, active systems, and protection from escort ships) will give the most survivability for a given price. Maximizing survivability of the arsenal ship subject to cost constraints will produce the numbers and types of system subcomponents necessary to meet a required level of survivability. This thesis focuses on the survivability of the arsenal ship and will provide a tool for the TSSE team. Validating the draft capabilities defined for the arsenal ship is not an objective.

The authors' recent participation in the Future Navy Game II provided insight for the model as well as another avenue for employing the model. We were invited to participate because of our familiarity with the arsenal ship program, and the game considered force calculi with differing numbers of arsenal ships. The seminar war game is part of a series of games sponsored by the Office of the Secretary of Defense Director of Net Assessment with the goal of examining the "operational and organizational

implications of a Navy precision-maneuver strategy against a large peer competitor in the 2020 timeframe." Results from the game series will be used in the Navy Long Range Planning Process and the PR99 assessment cycle. [Ref. 3] The participants are given a limited budget to buy advanced systems, and then play a scenario with their chosen systems. The game is evolving and becoming more analytical; recently small Excel spreadsheet models have been incorporated to aid in estimating mine warfare capabilities and strategic airlift scheduling. Operational logistics and the effects of attrition on naval forces are largely neglected. The sustainability portion of our model could prove useful for this and other future war games.

2. Threats and Employment Concept

The development of an arsenal ship reaffirms the Navy's resolve to meet changing post-Cold War threats. *Forward . . . From the Sea* outlines the Navy's response for the current world order. Emphasis is on projecting power from littoral regions with naval expeditionary forces to support joint operations. Surface ships with theater ballistic missile defense capabilities presumably foster conventional deterrence by discouraging the proliferation of ballistic missiles by our allies and adversaries. Such forces provide theater Commanders-in-Chief with rapid response, measures to control escalation, and a transition force able to act before land-based troops arrive in theater in the event of a major regional contingency. [Ref. 4]

According to the Capabilities Document, the arsenal ship will have two main missions: its primary mission is long-range strike and invasion stopping, and its secondary mission consists of tactical strike, fire support, battlefield interdiction, and battlespace dominance support (theater air defense, anti-air warfare, tactical ballistic missile defense) [Ref. 1]. A total force of five or six forward-deployed arsenal ships is envisioned. Arsenal ships will bolster the essential surge response capabilities and provide the theater Commander-in-Chief with a new operational maneuver element. These ships will carry an array of vertically launched weapons into littoral regions to support a land campaign. They will operate under the control and protection of multi-mission combatants, including Aegis cruisers and destroyers. Table 1 delineates representative target sets the arsenal ship

might engage, and Table 2 lists weapons the ship should be able to carry to counter each threat.

	Halt Invasion	Long Range Strike	Battlespace Dominance	Surface Fire Support
Complex Adaptive Armed Forces	Air Land Maneuve Battle Groups (e.g., OMGs)	National/Regional C4I Space Control	Manned A/C TBMs, UAVs Cruise Missiles SAM/AAA	Long-Range Artillery TBMs Logistics Assets
Armored Mech. Armed Forces	Armor-Heavy Comb. Arms Formations Divisions/BDEs	National and Regional C4I	Manned A/C TBMs SAM/AAA	Long-Range Artillery
Infantry Based Armed Forces	Armor/Mech. "Pure" units (BDEs/BNs)	Military Region District C4I	Manned A/C SAM/AAA	Medium-Range Artillery Logistics Assets
Internal Security Light Force	Transportation Railroads Trucking, Light Vehicles	National CMD Authority Military Concentrations	OP Bases Light A/C Coastal Patrol Craft	Logistics Assets Economic Asset Local Forces

Table 1. Target sets to be countered by arsenal ship from Ref. [A].

	Halt Invasion	Long Range Strike	Battlespace Dominance	Surface Fire Support
Complex Adaptive Armed Forces	SM-2/ATACMS-BAT SLAM TLAM-BAT TLAM-C	TLAM	ATACMS TLAM-C/D	ATACMS, SLAM TLAM-C/D Naval Gunfire (VGAS/SCRAM)
Armored Mech. Armed Forces	SM-2/ATACMS-BAT TLAM-BAT, SLAM Strike-SM	SM-2/ ATACMS-BAT TLAM-BAT SLAM Strike-SM	ATACMS TLAM-C/D	ATACMS, SLAM TLAM-C/D Naval Gunfire (VGAS/SCRAM)
Infantry Based Armed Forces	ATACMS SLAM Strike-SM	TLAM-D ATACMS-ER	ATACMS	ATACMS, SLAM TLAM-C/D Naval Gunfire (VGAS/SCRAM)
Internal Security Light Force	Naval Gunfire (VGAS/SCRAM)	TLAM-C	ATACMS Naval Gunfire (VGAS/SCRAM)	ATACMS Naval Gunfire (VGAS/SCRAM)

Table 2. Weapons to counter target sets from Ref. [1].

While the arsenal ship will add new capabilities, it will also face new threats. The littoral affords less space for operations, and the interface between sea and shore is where chaos is most prevalent. Fighting in the littoral subjects the ship to attacks from shore

with more advanced missiles. These factors result in less time to react to an incoming missile attack.

3. Design Philosophy

Conceptually, the arsenal ship is a force multiplier and should function as a cost-effective, remote missile magazine. The target unit price is $450 million or less with a ceiling of $550 million in FY 98 dollars The design life is thirty five years. The ship may be unmanned or manned with 50 or fewer people. Projections for the arsenal ship include approximately 500 vertical launch cells; targeting will be accomplished by other ships with Cooperative Engagement Capability (CEC) or similar links and an over-the-horizon (OTH) satellite link. The ship must carry sufficient fuel, consumables, and repair parts to support a ninety-day mission. It must also be capable of underway refueling and accommodating SH-60, V-22, and CH-46 aircraft with landing area and limited services [Ref. 1].

Regarding arsenal ship survivability, OPNAV N8 states:

> Though (the) arsenal ship will operate in any threat environment under the protective umbrella of battle force combatants, it must be survivable against 21st century anti-ship missiles, torpedoes, and mines. An affordable balance of active and passive on-board self defense features is necessary. Active self defense should be roughly equivalent to that of a combat logistics force ship. Passive defense should capitalize on the benefits of mass (tonnage) and innovative applications of multiple hull integrity and signature reduction [Ref. 1].

B. PREVIOUS STUDIES

Numerous studies have assessed the staying power of ships or proposed means to extend surface ships' ability to take hits and continue fighting. Incorporating stealth technology reduces susceptibility. Many sources, including the *Joint Munitions Effectiveness Manuals* cite the effectiveness of combat systems on susceptibility or survivability. A thesis by John Schulte [Ref. 5] reminds us that ships can be hit by ASCMs even with layered defenses. Further, empirical evidence and predictive equations

presented by Schulte and Humphrey [Ref. 6] show that current ships (with the exception of aircraft carriers) are not built to the Timex standard. They cannot "take a licking and keep on ticking." The Naval Surface Warfare Center (NSWC), Carderock Division analyzed the effectiveness of anti-vulnerability features in ship design and reports that the judicious application of hardening can greatly improve a ship's survivability without becoming cost prohibitive or losing much maneuverability. [Ref. 7]. In the Military Worth of Staying Power, Hughes states that through staying power, the military worth of a vessel is sustained and can be measured by the "maximum accurately delivered ordnance over the combat life of a warship" [Ref. 8].

A great deal of valuable work has been accomplished to date. Yet, no study consolidates the above issues in a cost effectiveness study of an arsenal ship's survivability and the task force's sustainabability.

C. MOTIVATION AND PROBLEM DEFINITION

The intent of the arsenal ship program is to provide a relatively low-cost platform to operate in the littoral regions. The unique mission of the arsenal ship and the new contracting procedures of the arsenal ship program require that we examine the possibility of a paradigm shift in ship design. The ship will carry minimal active self-defense systems, so studies involving the incorporation of stealth and hardening design features (such as selective armoring) are warranted. While not written specifically about the arsenal ship, the excerpt below from an article in the *Naval Engineers Journal* summarizes the problem well.

> There has been significant change in national policy and naval strategy over the last decade. We are now focused to provide forward presence in peacetime and make a critical contribution to power projection during the transition from crisis to conflict. Our recent experience indicates that these operations require force structures higher than we can sustain with our current investment accounts. The prospect for additional funding is dim, so we must become more efficient in the utilization of our resources. One of the keys is to determine the proper balance of stealth, EW and hard kill systems for our next generation of surface combatant.

> . . . By these means we can significantly improve ship staying power and overall mission effectiveness. . . . To accomplish these benefits, the Navy will need to develop new concepts for littoral operations and conduct tradeoffs where stealth, EW, and hard kill are balanced and not treated as mutually exclusive. The result will be force multiplying with a higher probability of mission success and survival. [Ref. 9]

Our objective is to develop a user-friendly model with which a decision maker can perform tradeoff analyses between adding specific systems and technologies to the arsenal ship and adding the protective services of other warships. The immediate goal of the model is to produce configuration alternatives with high arsenal ship survivability subject to a budget constraint. Since by definition the design alternatives are speculative at this stage, the model is formatted parametrically to facilitate easy updating. The model will also allow us to gain insight into and draw conclusions about the value of hardening and stealth features for naval ship designs in general.

Operational logistics is examined by exploring the sustainability of different naval component forces. The arsenal ship program would make little sense if the ship could not improve the naval component's time on station. A highly survivable ship contributes to a force's sustainability. Sustainability is not only measured in days on station, but also in terms of incoming missiles that can be countered, since the solution is scenario-dependent. This key aspect of logistical robustness has not received the attention it deserves.

Related to this issue is the projection in the *Surface Combatant Force Level Study* that around the year 2010 "The requirements for in-theater surface combatants exceeded the numbers needed to escort CVBGs and ARGs by a considerable portion" [Ref. 10]. The situation is true now more than ever. The surface fleet has down-sized while "Surface combatants have evolved into major combatants in their own right, able to make significant contributions to the joint campaign. . ." [Ref. 10].

Since VLS tubes are not currently replenished at sea, an arsenal ship task force may prove invaluable in the opening days of a conflict. The new platform may alleviate the need of removing warships from their tasks to rearm, which would require rotating

replacement ships into the theater. Comparisons will be made between forces with and without an arsenal ship, and an arsenal ship missile load-out that maximizes the naval component's sustainability for a major regional contingency (MRC) will be offered.

This thesis focuses on the threat to an arsenal ship from anti-ship cruise missiles (ASCMs), which are presumed the most serious and likely threat in the littoral arena. Since 1970, cruise missiles have caused more damage to warships and shipping than all other threats combined. Obviously ASCMs are not the only threat. Mines and torpedoes are nemeses that must be dealt with. While a ship can be hardened to withstand damage from contact torpedoes, under hull torpedo or mine explosions are threats not easily designed against. Other weapons, including gunfire and bomb raids on the ship can be approximated in the model by changing the input ASCM explosive weight. The methodology of the model can be applied to mine and torpedo threats, but even if effective countermeasures could be traded-off, the authors believe that synergistic effects of vastly different threats cannot be modeled responsibly or reliably. A pragmatic approach to coping with the torpedo threat is to assume that ASW assets are required and deduct their cost from the top of the available budget. The mine threat can be minimized by collecting intelligence observations, avoiding areas known to be mined, and maintaining current surveys of underwater characteristes for areas of interest (Q-route surveys).

II. MODEL DEVELOPMENT AND PHILOSOPHY

A. SURVIVABILITY EQUATION DEVELOPMENT

This section defines requisite terms, states assumptions, and derives our survivability equation. The survivability equation is the base measure of effectiveness applied in our iterative survivability model which can then be compared against cost. Detailed derivations of individual probabilities appearing as multiplicative factors in said equation appear later.

A naval ship's <u>survivability</u> is "the capacity of a surface ship to avoid and/or withstand a man made hostile environment while performing its mission" [Ref. 11]. Hence survivability depends on susceptibility to attack and vulnerability once stricken.

<u>Susceptibility</u> is defined as the probability of being hit (P_{hit}) and represents "the inability of a ship to avoid the sensors, weapons, and weapons effects of that man-made hostile environment" [Ref. 11]. The susceptibility of the arsenal ship is a function of factors internal and external to the ship. If escorted by surface combatants, the number and types of ships in formation are important. Escorted or not, active and passive defensive systems on the arsenal ship affect susceptibility. For example, the susceptibility of an escorted arsenal ship under missile attack depends on the effectiveness of the defending escort's weapons. If missiles leak through the escort's protective umbrella (called <u>leakers</u>), the arsenal ship's point defense systems and degree of stealth factor into its susceptibility.

<u>Vulnerability</u> is the conditional probability that a ship is killed given that it is hit ($P_{kill|Hit}$) by a bomb, missile , torpedo, or mine [Ref. 11]. Values for ($P_{kill|Hit}$) depend on physical characteristics of the ship and incoming weapon employed. Historically, studies of ship vulnerability consider one or both of two degrees of vulnerability — the probability that a ship is rendered not mission capable or the probability that a ship is sunk. **This thesis only considers mission kills.** Hence, vulnerability is defined more narrowly as the conditional probability that the arsenal ship is rendered not mission capable by an incoming projectile.

The arsenal ship is unique in that it requires input from CEC capable ships or satellites to accomplish its mission. Consequently, the arsenal ship can suffer a mission kill if it remains intact but has no platform nearby to control its weapons. The effects of escort attrition are considered significant, are estimated in the model, and will be addressed later.

In the purest sense, vulnerability is assessed by the ratio of hits the ship sustains to its staying power — the number of hits from a specified weapon required to affect a mission kill (N_A). Applying the results of Richard Humphrey's *Warship Damage Rules for Naval Wargaming*, staying power can be calculated as: $\mathbf{N_A = C(D/H_E)^{1/2}}$,where C is a fitted constant based on an comprehensive study of ships damaged in World War II; D is the displacement of the arsenal ship in tons, and H_E is the explosive weight of the projectile in pounds [Ref. 6].

A more recent thesis by John Schulte derived an alternative formula for staying power [Ref. 5]. As shown Table 3 below, both methods produce similar results. Schulte's thesis considered Exocet missile and equivalents, so, for comparison, we used the Exocet's explosive weight in Humphrey's equation. We incorporated the Humphrey equation into our model because it considered larger ships. The Schulte thesis studied 222 cruise missile firings, but no targeted ship exceeded 7000 tons.

Ship Type	Displacement (tons)	Humphrey N_A	Schulte N_A
FFG-7	5500	1.51	1.74
DDG-51	8300	1.86	1.97
DD-963	9100	1.95	2.02
CG-47	9600	2.00	2.06
Arsenal Ship	20000	2.89	2.52
Arsenal Ship	40000	4.08	3.02

Table 3. Comparison of staying power calculation results using an Exocet equivalent net explosive weight.

The goal is to assess an arsenal ship's survivability. We define survivability (S_A) as the arithmetic complement of the probability of a mission kill (P_{kill}). The probability of a

mission kill is the product of the arsenal ship's susceptibility and vulnerability. Therefore, arsenal ship survivability against a missile is: $\mathbf{S_A = 1\text{-}(P_{hit})(P_{kill|Hit}) = (1\text{-}P_{kill})}$.

Expressed in terms of the number of notional missiles fired and the resulting number of leakers, arsenal ship survivability can be calculated as: $\mathbf{S_A = 1\text{-}(MQ/N_A)}$, where M is the number of well-aimed missiles; Q is the probability of leakers; and N_A is the staying power in hits. Hardness features can be incorporated into the ship design that will increase the staying power by a factor of H. Assuming missile firings are independent, identically distributed events with **P(leaker) = Q**, then leakers are distributed binomially with parameters M and Q. Therefore, the expected number of leakers is: **E[leakers] = MQ** and the expected damage to the arsenal ship is: $\mathbf{E[damage] = MQ/(N_A H)}$.

Q can be decomposed into probabilities for individual events as shown in Table 4. For a leaker to strike the arsenal ship the following must all occur.

EVENT	ASSOCIATED PROBABILITY
Defending escort does not kill incoming missile	Q_{AE}
Missile not affected by arsenal ship stealth	Q_{AS}
Arsenal ship soft kill measures fail	Q_{AE}
Arsenal ship point defense systems are ineffective	Q_{AA}
Note: Associated probabilities are derived below.	

Table 4. Probabilities Contributing to a Leaker Damaging the Arsenal Ship

The resultant equation for survivability is: $\mathbf{S_A = 1\text{-}(MQ_{AE}Q_{AS}Q_{AP}Q_{AA}\,/(N_A H)\,)}$

B. KILL PROBABILITY DERIVATIONS

In this section the parameters for determining the survivability of the Arsenal ship are given.

<u>INDICES</u>

- i Soft kill systems
- j Hard kill systems
- t Escort types (ship classes)

<u>UNIT QUANTITY</u>

- n_t Number of units of type t

SOFT KILL SYSTEMS

These systems conduct soft kills on a shot. Systems like ESM and Chaff/Torch divert a shot after the arsenal ship has been targeted by the ASCM.

HARD KILL SYSTEMS

Point defense systems physically kill leakers. The Mark 15 Vulcan Phalanx Close-in-Weapon-System CIWS, rolling airframe missile (RAM), 5"54 gun, and Evolved Sea Sparrow (ESS) are examples.

ESCORT TYPES

Cruisers (CG-47 Class - Ticonderoga), Destroyers (DDG-51 Class - Arleigh Burke), (DD-963 Class - Spruance), Frigates (FFG-7 Class - Oliver Hazard Perry).

PROBABILITIES OF KILL

P_{AE} Probability that escorts can kill an incoming shot.

Note: P_{AE} is a representation of the aggregate probabilities. The value varies in the simulation. Details of the iterative approach appear in Chapter III.

P_i Probability that a system of type i can effect a soft kill of an incoming shot.

P_j Probability that a system of type j can kill an incoming shot.

P_m Probability that stealth precludes an incoming shot.

MISSILE LEAKER PROBABILITIES

Q_{AE} Probability that the arsenal ship is not protected by the defending escort.

$$= \left[\left(1 - P_{AE}\right) \right]$$

Q_{AS} Probability that stealth does not preclude an incoming shot.

$$= \left[\left(1 - P_m\right) \right]$$

Q_{AP} Probability that the arsenal ship does not soft kill an incoming shot.

$$= \left[\prod_i \left(1 - P_i\right) \right]$$

Q_{AA} Probability that arsenal ship point defenses do not kill an incoming shot.

$$= \left[\prod_j \left(1 - P_j \right) \right]$$

C. COSTING ASSUMPTIONS

Since the procurement, operating, and support costs of an arsenal ship are as yet unknown, we consider the incremental cost of adding systems over the base ship in our study. A base ship is an arsenal ship without any defensive systems. We believe that we can more accurately estimate these incremental costs than the cost of a conceptually new ship itself.

By conducting the tradeoff analysis using incremental costs, we also avoid some difficult questions of arsenal ship O&S costs. These will depend on several unresolved issues, the two most significant are:

1. The ship's manning level is unknown, and a rotation scheme such as blue-and-gold crews may be used.

2. While desired capabilities have been published, how the ship will operate has not been established.

While most calculations in the model do not require the base cost of the arsenal ship, our estimates for the price of adding stealth and hardening do. In these instances, we use the target cost of $450 million reported in the Arsenal Ship Program Solicitation. This figure, which may be high, still affords $100 million for procuring defensive systems based on the ceiling established in Ref A. Details of cost calculations are provided in Chapter IV.

III. MODEL FLOW AND FUNCTION

The Arsenal Ship Tradeoff Analysis Model is designed to track configurations, costs, survivability and sustainability. It is not intended to be a combat simulation. Only those elements required to predict expectations of the desired output are incorporated in the model.

The Arsenal Tradeoff Analysis Model overview in Figure 1 is actually comprised of two smaller sub-models. The Survivability sub-model aids decision makers in determining the best combination of arsenal ship self defense features and escorts. The Sustainability sub-model tests a specifically designed arsenal ship deployed within a task force to determine the force's sustainability. Both sub-models are described below.

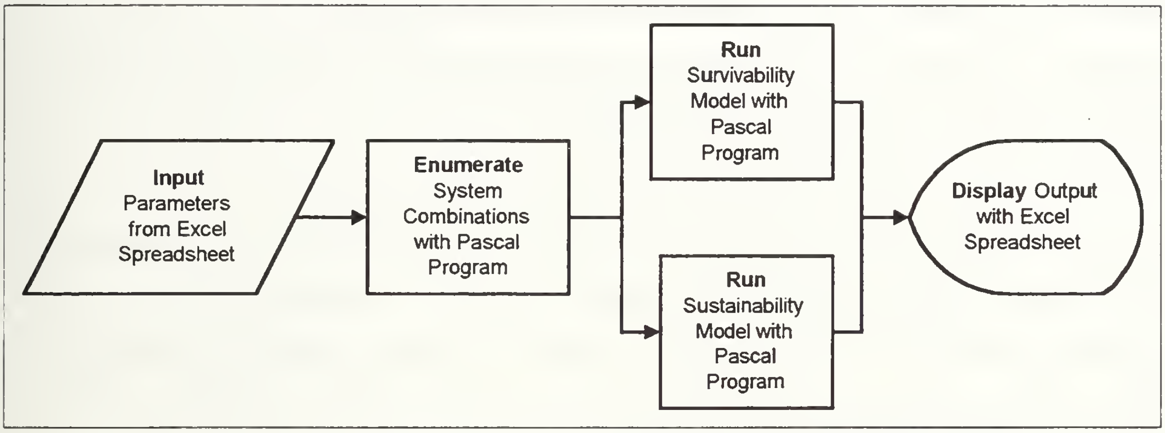


Figure 1: Flow of the Arsenal Ship Trade-Off Analysis Program.

A. SURVIVABILITY SUB-MODEL

1. Input Section

The Survivability sub-model consists of a spreadsheet input section, two Pascal programs, and a spreadsheet output display. In the input section, the user enters parameters, scenario, and limiting factors for consideration in generating arsenal ship configurations. After all inputs are made, the user is prompted to save the parameters to a data file which is formatted for use by other programs in the model. Chapter IV will cover the inputs in greater detail, and the User's Guide (Appendix C) describes the input procedures.

2. Enumeration Program

This second step in the survivability model uses a Pascal program to enumerate all possible combinations of arsenal ship self-defense features and escorts with the parameters from the input section. It stores them in a file formatted for reading by the Survivability program.

3. Survivability Program

The third step is to run the Survivability program -- also coded in Pascal. The model calculates the survivability and cost of an arsenal ship based on the defense features and escort variables input by the user. In addition, the model determines the task force's effectiveness in defending the arsenal ship and the number of SAMs remaining on the arsenal ship. Each major component in Figure 2 will be discussed, highlighting the assumptions and methodology. The enumeration file is opened, and the first system combination is selected. Using the Excel data file, each combination of systems is run through the survivability program outlined in the following pages. The output is a file listing the systems which meet the limiting criteria.

a. Designate Defender

If there are escorts, the most capable AAW platform will be chosen as the task force defender (see Figure 3). If a defender has already been designated in a previous run, it is re-confirmed as a mission capable defender. A mission capable defender is one that has additional staying power and SAMs.

Our model assumes that the defender will always be positioned between the threat and task force, hence, attack geometry is optimal. In reality, CEC and stationing tactics promote coordinated fire between defenders. This reduces multiple ship engagements, overkill and wasted ordnance. Hence our assumption that the best positioned defender is selected to engage the incoming missile is reasonable.

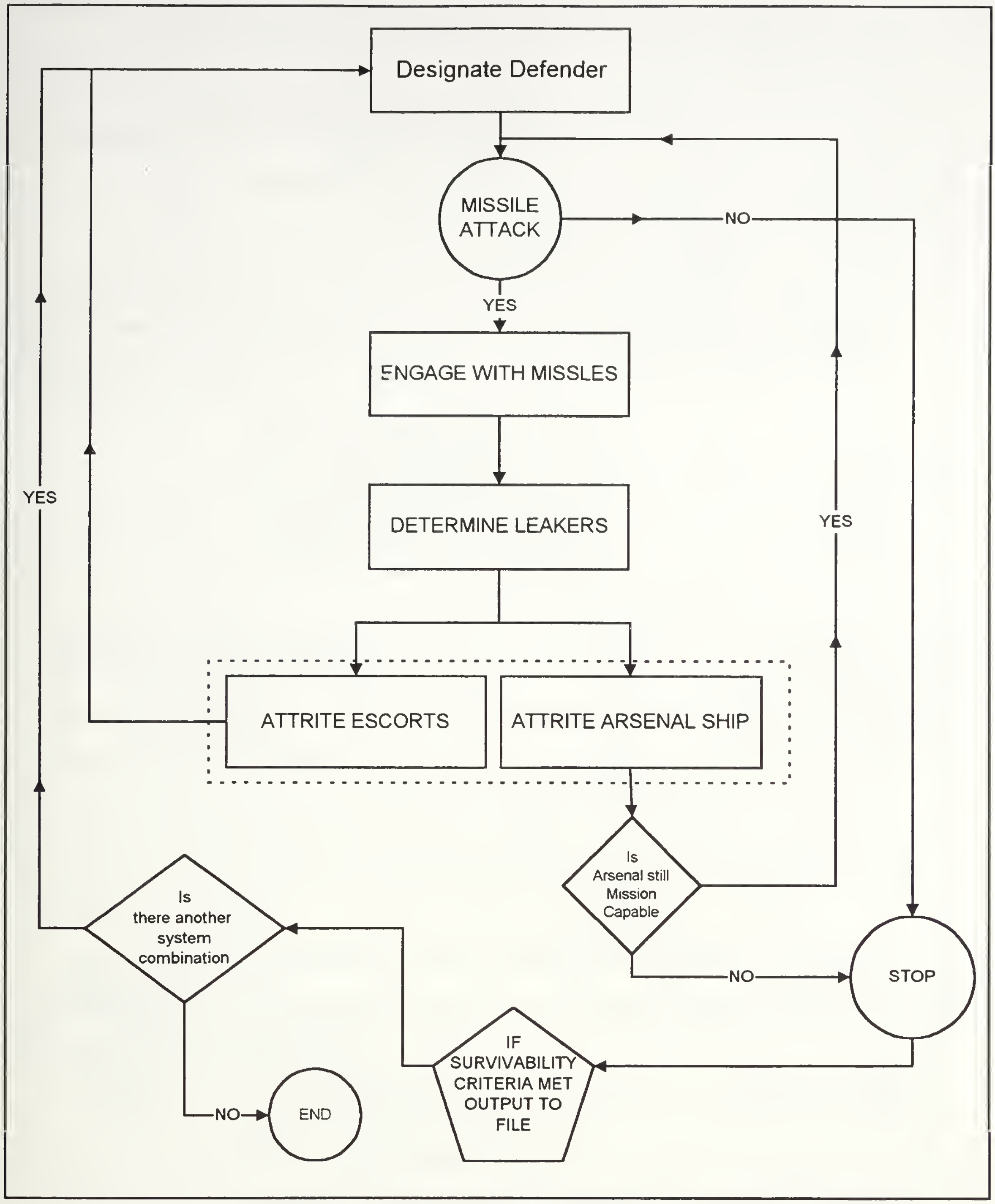


Figure 2: Major components and flow of the Arsenal Ship Survivability Model

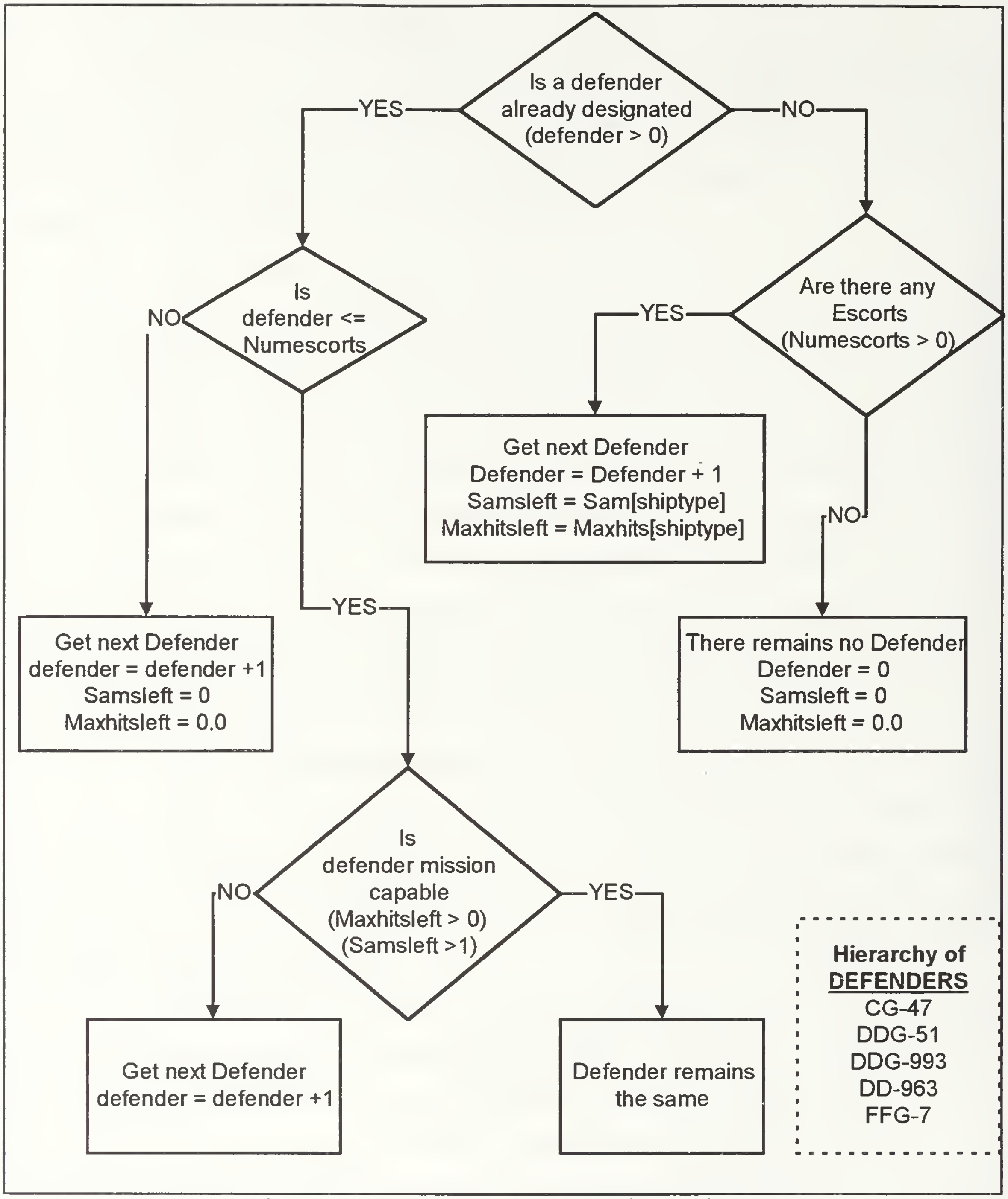


Figure 3: Model flow of Designating Defender

After each missile shot, the defender's cumulative damage is checked. If the accumulated damage does not exceed its staying power and it has SM's left, then the escort remains the defender for the next missile attack.

b. Missile Attack

Missile attacks are discrete independent occurances with the time between events such that they do not saturate a defender's ability to engage incomings. The user inputs the number of missiles to be engaged by defining a scenario that identifies the number of missiles per wave per day.

c. Engage With Missiles

In this component the defender engages the incoming missiles with SAMs (see Figure 4). If the defender has a sufficient number of missiles, it will engage the inbound using a shoot-shoot-shift firing policy. This policy is chosen based on a littoral scenario where the defender only has time for one engagement. This means every incoming missile will be engaged with two SAMs and the defender will not shoot at the same incoming missile even if it survives the initial salvo. An Aegis defender without missiles will engage the incoming missile with arsenal ship missiles via the CEC link. When the arsenal ship and Aegis defender are empty, a new defender is chosen. A non-Aegis defender (not CEC capable) without missiles is considered not mission capable, and a new defender is chosen.

After the inbounds are engaged, the number of leakers is determined. The leaker formulation is given below. The next chance to defeat the leakers happens with the task force's point defense systems.

$$\text{Leakers} = (1\text{-PK}_{\text{SAM}})(1\text{-PK}_{\text{SAM}})$$

d. Determine Leaker Allocations

This component allocates leakers among the task force by radar cross section (RCS) as shown below and in Figure 5. Simply stated, a unit's RCS percentage of the whole task force's RCS determines the portion of leaker to allocate to that unit. Two

$$\text{ArsenalAllocation}[\text{AA}] = \frac{\text{ArsenalRCS}}{\sum_i \text{EscortRCS}_i + \text{ArsenalRCS}}$$

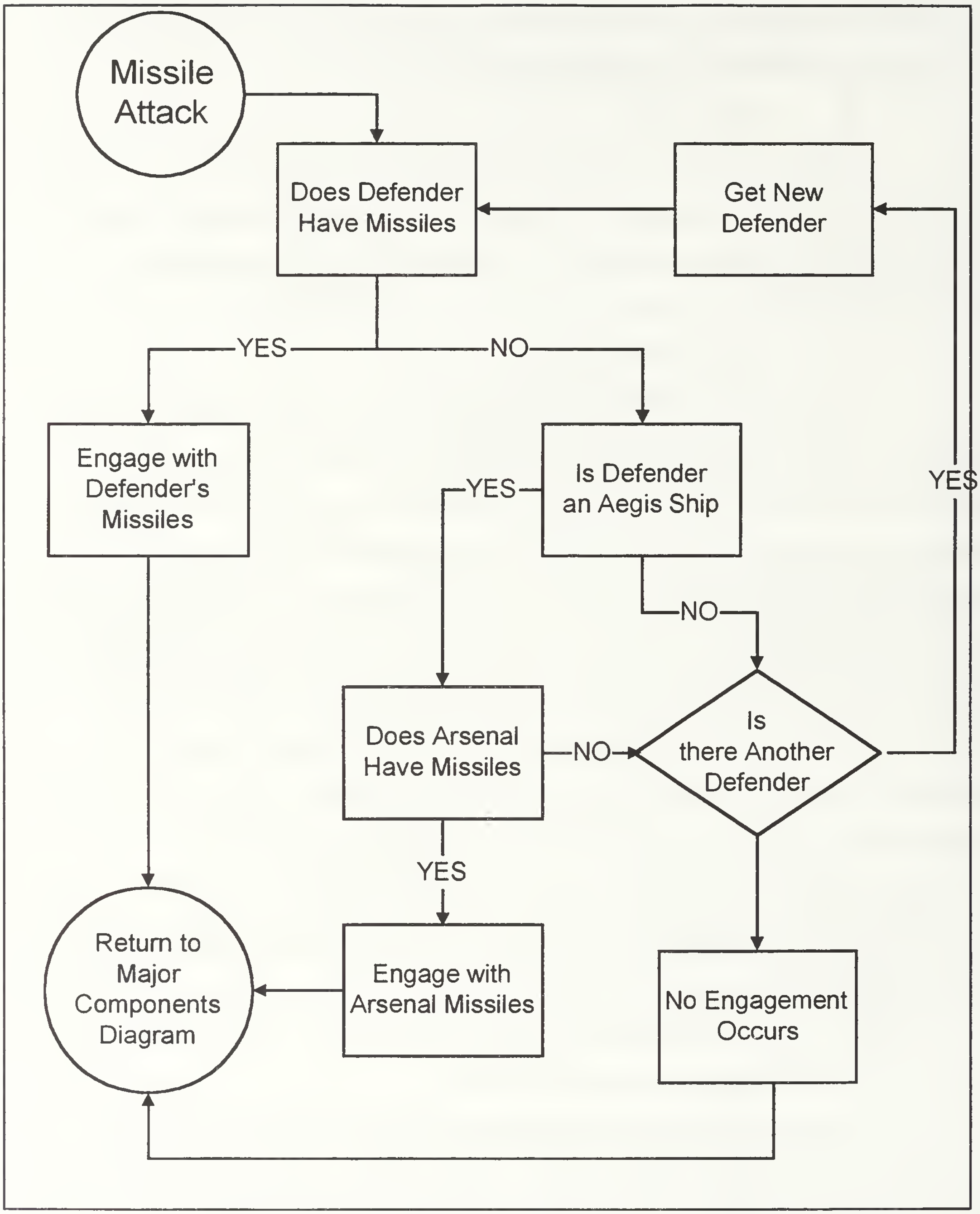


Figure 4: Engagement with Missiles by the defender

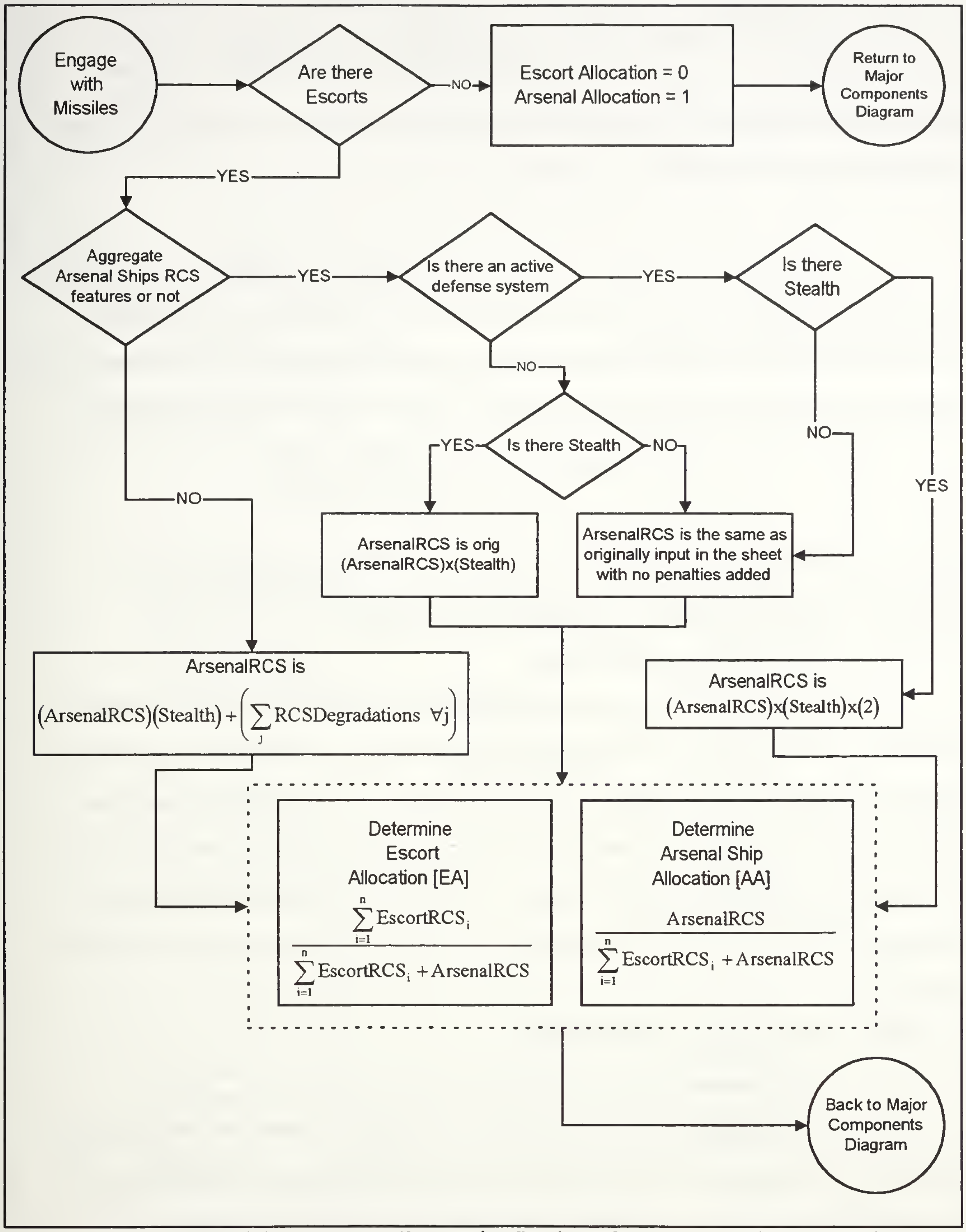


Figure 5: Model component Determine Leakers for escorts and arsenal ship

$$\text{Escort Allocation}[EA] = \frac{\sum_i \text{EscortRCS}_i}{\sum_i \text{EscortRCS}_i + \text{ArsenalRCS}}$$

methods of determining radar cross section are available. They are represented in Figure 5 and described in the input section of Chapter IV.

e. Attrite Escorts

Referring to Figure 6, the model attrites on a fair share basis. The EA is sub-allocated among the escorts, see formulation below. Each escort then engages its share of leakers with their point defense systems. The damage incurred from leakers on all available escorts is applied to the current defender. After a defender sustains damage,

$$\text{Escort's Fair Share of EA} = (EA)\frac{\text{EscortRCS}}{\sum_i \text{EscortRCS}_i}$$

its cumulative damage is compared to its staying power. If the damage exceeds the staying power, another defender is chosen (if there is another).

f. Attrite Arsenal Ship

Like the escorts, the AA is subjected to the arsenal ship's point defenses. See Figure 7. The escorts have a single aggregate PK factor, whereas the arsenal ship's PK depends on the system combination being considered. Arsenal ship damage is that amount of AA which defeats the hard kill, soft kill and anti-vulnerability features of the ship. After the arsenal ship sustains damage its cumulative damage is compared to its staying power. If the damage exceeds the staying power, the arsenal ship is considered a mission kill.

B. SUSTAINABILITY SUB-MODEL

1. Input Section

This model evaluates the long-run effects of an arsenal ship's survivability on the battle force's sustainability. The input section consists of designating a specific arsenal ship configuration, task force composition and arsenal ship's limiting (desired) survivability level.

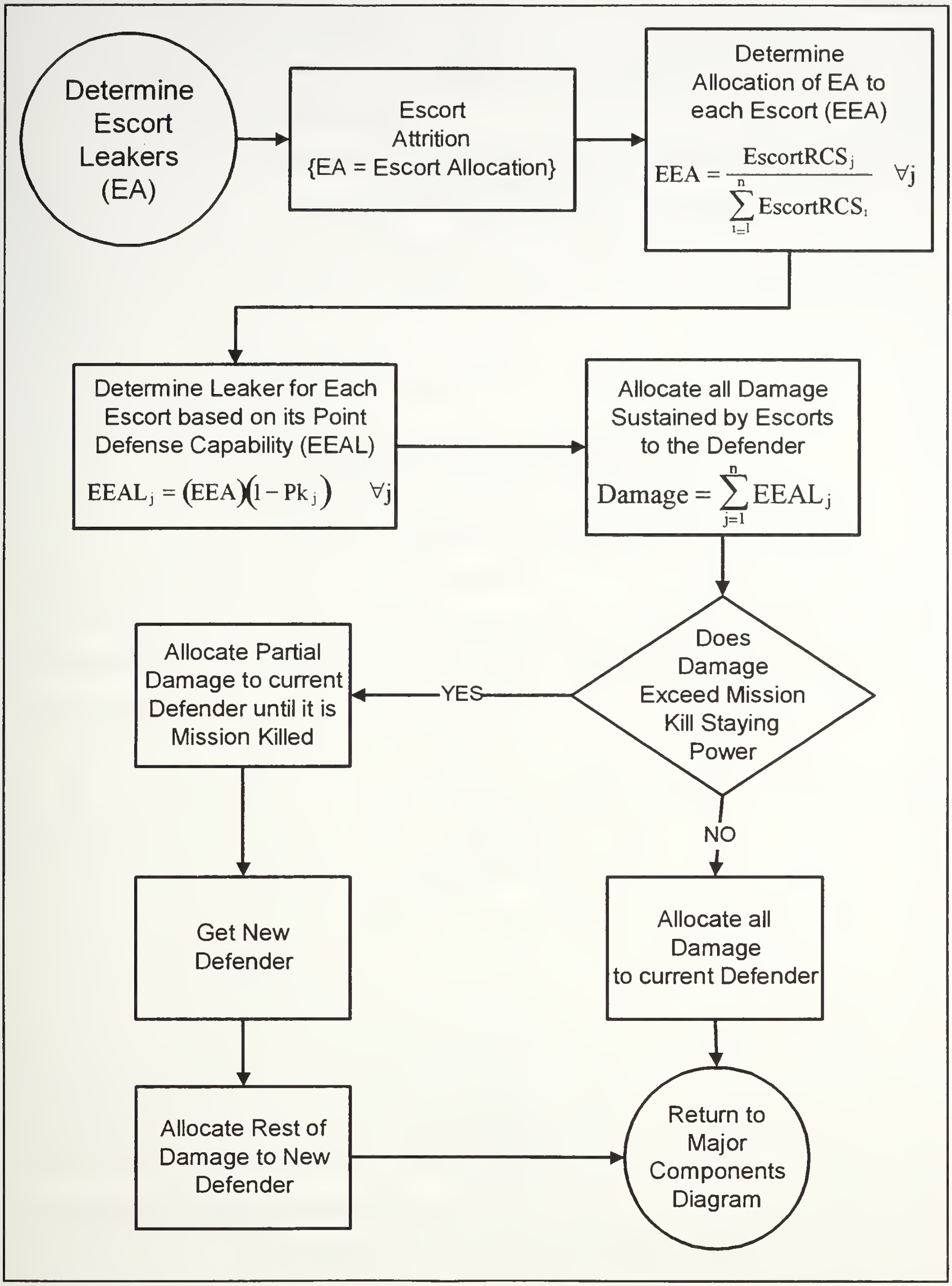


Figure 6: Model component Attrite Escorts

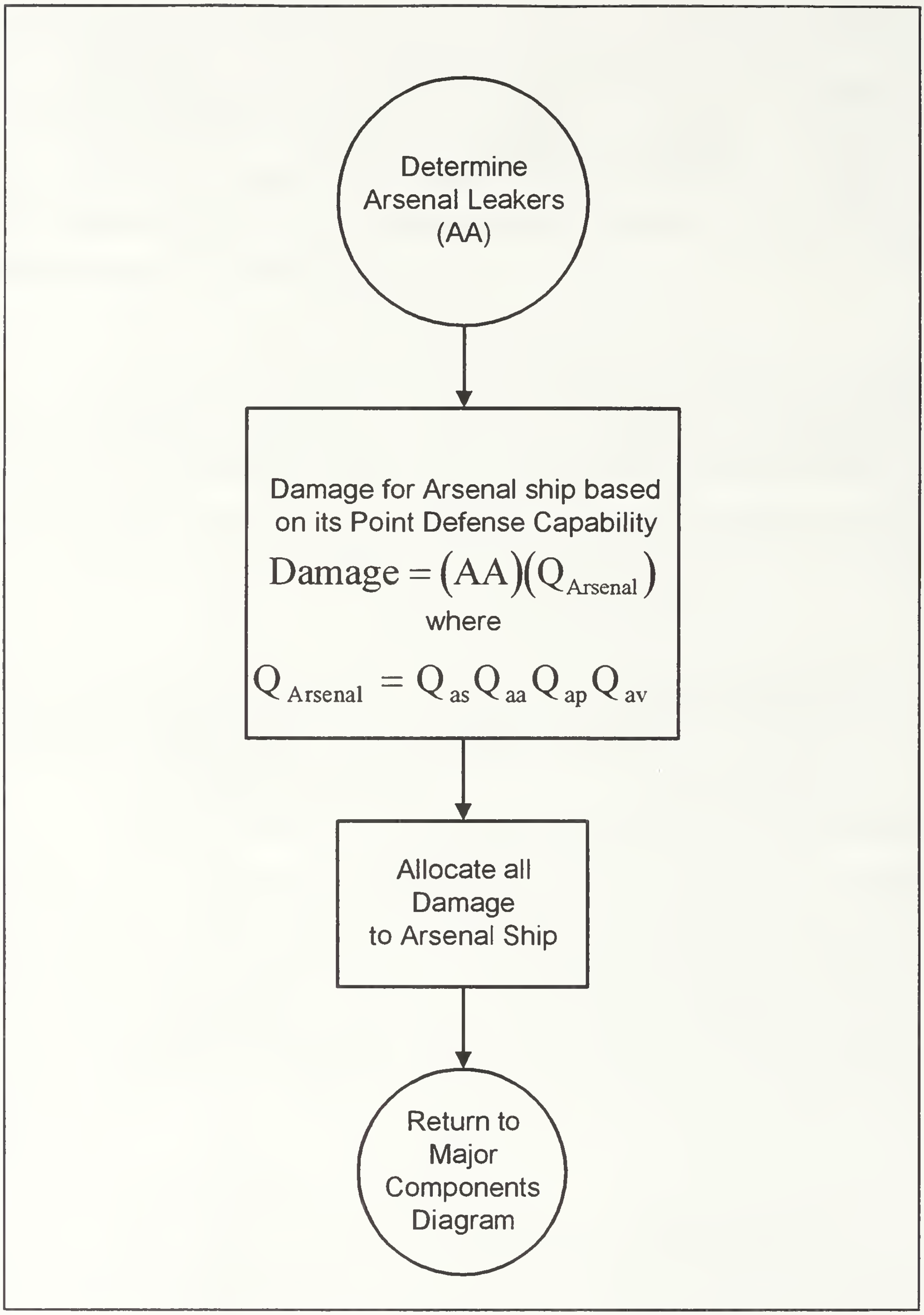


Figure 7: Model component Attrite Arsenal Ship

2. Enumeration Section

This program is identical to the Survivability model's enumeration program.

3. Sustainability Program

The major components of this program are similar to those in the Survivability program (see Figure 2). The difference is that the arsenal ship's configuration is now constant and the number of missiles the task force can withstand before the arsenal ship reaches its limiting survivability is variable. Differences from the Survivability program are outlined as follows.

a. Designate Defender

This component remains the same. See Figure 3.

b. Missile Attack

In this component, the number of missiles launched at the task force becomes variable, unlike in the Survivability model where the features were the variables and the maximum number of incoming missiles was fixed. The number of missiles a task force can endure is representative of time on station. Missile attacks continue so long as there is a ship in the task force not OOA.

c. Engage with Missiles

This component remains relatively the same as in Figure 4, except for code which records the status of the defender when it becomes OOA.

d. Leaker Determination

Same as in the Survivability model. See Figure 5.

e. Escort and Arsenal Attrition

Missile attacks and attrition occur so long as there are mission capable ships in the task force. The survivability limiting criteria entered by the user apply to the arsenal ship **only**. The escorts fight until they are OOA and the arsenal ship fights until it reaches the limit of its staying power. The program runs until the task force is OOA. The model results are displayed on screen and written to a file.

IV. MODEL INPUTS

Flexibility and power are demonstrated in the input section. The user must input susceptibility and vulnerability features of the escorts and arsenal ship. Each type of input will be discussed and then followed with the values used to exercise the model to investigate the relative values of survival attributes. Results will be presented in Chapter V.

A. ESCORT SHIPS

The user may consider the defensive effectiveness of escorts currently or potentially in the Fleet and their impact on the arsenal ship's survivability. Since this model focuses on the ASCM threat, the escorts must have the ability to defend against ASCMs. Ticonderoga Class (CG 47), Arliegh Burke Class (DDG 51), Kidd Class (DDG 993) and Oliver Hazard Perry Class (FFG 7) ships are used. SC-21 variants or other ships can be used if the user has characteristic data. The following inputs are required of each escort type.

1. Quantity

A minimum and maximum number of each candidate escort type is required. An input of '0' for minimum and '2' for maximum means that the model will enumerate all permutations with zero, one and two of this escort type. To fix or 'hardwire' the number of an escort type, set the minimum and maximum numbers the same. For example, changing the Ticonderoga minimum and maximum to '1' and '1' will force the model to consider one CG-47 in each permutation. This thesis examines the quantity inputs shown in Table 5 for our run of the model.

2. Single Salvo Kill Probability

AAW single salvo kill probability (PSSK) is the chance an escort will destroy an incoming ASM with one SAM salvo. This probability accounts for incomings with direct (the escort itself is the target) or crossing (another ship in the task force is the target) flight paths. As explained in Chapter III, this model uses a shoot - shoot - shift SAM firing doctrine by the escort designated as defender.

Since an escort is more likely to kill an incoming vice a crossing target, we assume an Aegis ship PSSK of .96 and .84 respectively. A mean of .91 is used for PSSK. This is consistent with other unclassified studies which estimate an Aegis ship's single shot effectiveness between the ranges of 0.7 and 0.8 [Ref. 8, p. 34]. Inputs for non-Aegis ships are assumed to be lower, due to their lower detection and targeting capabilities. Ship PSSKs are given in Table 5. Components in Table 5 that have not been discussed yet will be detailed in what follows.

Ship Class	Min Qty	Max Qty	PSSK	# SAMs	PD PK	Days	Disp (tons)	RCS
CG-47	0	2	0.91	70	0.503	90	9,600	49,896
DDG-51	0	2	0.91	50	0.503	90	8,300	24,998
DDG-993	0	1	0.75	56	0.394	90	9,800	51,515
FFG-7	0	2	0.64	21	0.394	90	3,700	33,069
Arsenal Ship				284			20,000	36,750

Table 5: Model input values for the escorts

3. Number of Escort SAMs

SAM load out for each escort was calculated using the notional VLS load out data from Ref. 10. On the average, 55.5% of the missiles per ship were allocated to SAMs and 44.5% were allocated to strike. Table 5 shows the number of SAMs (# SAMs) used throughout this thesis. This leaves 56, 40, 45, 37, 228 strike weapons for the CG-47, DDG-51, DDG-993, FFG-7, and arsenal ship respectively.

4. Cost

The marginal cost of protecting an arsenal ship comes from defense features contained within the arsenal ship and from escorts which provide protection services. Both must be charged to the overall cost of the arsenal ship program. The model considers costs on an annual lifecycle basis. The annual lifecycle cost is obtained by dividing procurement cost by lifecycle length (in years) and adding the annual expected O&S cost.

Ship procurement data was obtained from Data Search Associates' annual "U. S. Weapon Systems Costs" publications [Ref. 12, Ref. 13]. Operational and Support costs are published by the Naval Center for Cost Analysis' "Visibility and Management of Operating and Support Costs (VAMOSC)" Program Office [Ref. 16]. This thesis assumes each escort has a lifecycle of 30 years. The procurement cost is determined by taking the

total program cost (sum of RDT&E, unit cost, and other costs) and dividing by the number of ships procured. O&S cost is the total O&S costs (includes operational, manpower, maintenance and indirect O&S costs) for all ships in the class divided by the number of ships in the class. Table 6 gives a breakdown of costs for each escort in 1996 dollars using a 3% inflation rate when required.

Ship	Procurement Cost ($)	O&S Cost ($)	Life Cycle Years	Annual Lifecycle Cost ($)	Annual Escorting Cost ($)
Tico (CG47)	$1,237,038,179	$28,814,948	30	$70,049,554	$14,681,619
Burke (DDG51)	$1,063,900,596	$21,500,976	30	$56,964,329	$11,939,099
Kidd (DDG993)	$469,262,553	$25,156,840	30	$40,798,925	$8,551,008
Perry(FFG7)	$298,513,074	$17,077,516	30	$27,027,952	$5,664,763

Table 6: Escort annual lifecycle cost input in dollars per year.

5. Displacement

Full-load displacements in tons, provided from Jane's Fighting Ships [Ref. 14] are input (see Table 5). These values contribute to determining staying power as defined earlier. A baseline estimate of the arsenal ship's displacement is required. The baseline is a stripped-down, typically-designed, naval ship such as an amphibious ship. Accepted arsenal ship displacement predictions are 20-40 thousand tons. We choose 20 thousand tons to be conservative in our staying power calculations. The weight of hardening and other features are not added, since their contribution to staying power is contained in their PKs. This avoids a 'double dipping' effect.

6. Escort Time

How long (in days per year) will escorts be required to provide the survivability level desired for the arsenal ship? The method of deployment and operational tempo will significantly affect this value. For example, if the arsenal ship deploys continuously with a carrier battle group (CVBG), the cost of escort services should contain the costs of all escorts in the CVBG. Escort time would be shared between the arsenal ship and carrier since both are receiving the same services. We assume there will be times when the CVBG will split into smaller task groups — this is frequently the case today. The arsenal ship, however, could deploy overseas like the maritime prepositioned force (MPF) ships. In this case, a round number of 90 days per year could be used as the length of time the arsenal ship will require protection; otherwise it would be pier side or training in non-

hostile waters. Our methodology charges the escorts services solely to the arsenal ship. It is evident that the fraction of the escort's life time (hence cost) that should be charged to the arsenal ship task force is both a sensitive parameter and difficult to estimate. We chose 90 days per year. Therefore, one-quarter of the escort's life cycle cost is used for tradeoff analysis.

7. Mission Time

This is the percentage of escort time a ship actually conducts its AAW mission. Beside providing escort services, an escort requires time to conduct maintenance, training and replenishment which conflict with the AAW mission. The arsenal ship is only charged for the time AAW services are provided, and not the full time the escort is attached to the arsenal ship. We use 85% — the same as the CNO (N86) *Surface Combatant Force Level Study, Requirements for Joint Warfare* which assumed a 15% "logistics factor" [Ref 10, p 4-9].

8. Self Defense

As discussed in Chapter III, a defender is designated from the task force to provide first layer AAW defense with a SAM firing doctrine of shoot - shoot. Any leakers at that point are assumed to be too close to engage with systems other than self defense soft kill and hard kill point defense.

Most studies consider a defense in-depth methodology where all layers of defense have a chance of countering the incoming missile attack. This equates to ASCM kill probabilities of 99% or higher [Ref. 8, Ref. 15]. These studies, however, assume that enough time and space exist for an Aegis system, for example, to detect and engage with all its systems. Naturally, the hits on ships depend on more variables than test range point defense effectiveness.

In this thesis, a layered point defense is calculated as a parallel system. A CG-47 class ship has ESM/SRBOC, CIWS and ESS (each of these is explained later). The total PK is given in the equation below.

$$PK_{Total} = 1-(1-P_{ESS})(1-P_{ESM})(1-P_{CIWS})$$

$$PK_{Total} = 1-(1-.7)(1-.325)(1-.575) = .914$$

Assuming that incoming missiles will be detected in time for only one SAM salvo per missile by the defender, each ship will defend against leakers with its point defense systems. In the case of the escorts, the defense in depth methodology is applied (computing defense systems in parallel), but an effectiveness weight value is applied. The weight value applied comes from the Schulte thesis [Ref 5], since his data showed that for all the missiles shot at defended ships after 1982, there was a 45% chance of a hit. The study discovered that all but one missile which did not hit the ships, were defeated by passive defense systems. The 45% chance of being hit equates to a 55% effectiveness of point defense systems (soft and hard kill). Many other variables such as scenario, surprise, time of detection, environmental factors, and human factors affect the outcome of a missile attack. These "fog of war" variables are inherent in the combat data reported by Schulte. Consequently, our 55% effectiveness weight factor for the combined point defense systems is considered realistic.

Applying the effectiveness weight value results in the ship's final adjusted point defense (PD) PK, which does not overestimate self defense capabilities. The results for all escorts are given in Table 7.

$$PK_{Adjusted} = (PK_{Total})(weight) = (.914)(.55) = .503$$

Ship	Esm/SRBOC	ESS	CIWS	Total PK	Eff Weight	Adjusted PK
CG-47	0.325	0.7	0.575	0.914	0.55	0.503
DDG-51	0.325	0.7	0.575	0.914	0.55	0.503
DDG-993	0.325	n/a	0.575	0.713	0.55	0.394
DD-963	0.325	n/a	0.575	0.713	0.55	0.394
FFG-7	0.325	n/a	0.575	0.713	0.55	0.394

Table 7: Point defense effectiveness values (PD Pks) for the escort ships.

9. Radar Cross Section (RCS)

This input represents the escorts' signature emissions (detailed in the definition of stealth in Appendix B) that incoming missiles can target on. RCS is used as a representation of stealth. Assuming that the ship design is balanced — that is to say no detectable emission is grossly more discernible than another — the RCS approximation method is sufficient for our analysis. As discussed in Chapter III, this input is the basis on

which leakers are allocated amongst ships. The actual numbers are not crucial for the model, but rather the ratios between platforms and arsenal ship are important.

Since a ship's RCS is classified, this thesis will use length, freeboard and mast height to compute representative RCS values. Figure 8 shows how RCS is actually calculated . Using this methodology, RCS is the sum of the superstructure area

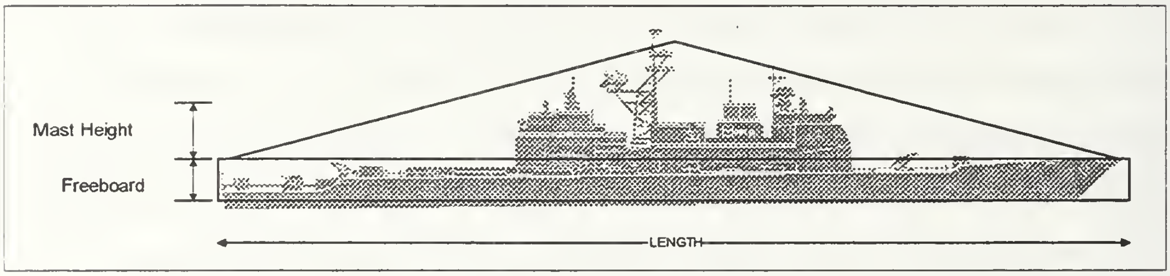


Figure 8: Escort RCS

(1/2 x Length x Mast Height) and hull area (Length x Freeboard). RCS figures are given in Table 8. Assumed arsenal ship dimensions are 700ft length, 15ft freeboard and 75ft mast height. This suggests that our notional arsenal ship will ride low in the water. The Arleigh Burke Class destroyers were designed with stealth features, so the RCS used is assumed 1/2 that of a typical destroyer built without stealth.

Ship	Length	Freeboard	Mast Height	RCS
Tico (CG47)	567	20	136	49,896
Burke (DDG51)	505	25	148	24,998
Kidd (DDG993)	563	20	143	51,515
Perry(FFG7)	453	15	116	33,069
Arsenal Ship	700	15	75	36,750

Table 8: RCS inputs into model based on Length, Freeboard and Bridge Height.

Additional RCS is incurred when topside systems are added to the base arsenal ship. For each feature considered, there is an 'additional RCS' input. Our RCS values are based on the equation below. Height values were obtained from the Naval Warfare Publications (NWP-65 series).

$$\text{Additional RCS} = (\text{Length}_{\text{Arsenal}} \times \text{Height}_{\text{Feature}}) \times 0.5$$

B. SUSCEPTIBILITY FEATURES

Soft kill, hard kill, and defensive measures can be employed to reduce the susceptibility of the arsenal ship. Soft kill features can confuse or 'draw off' an incoming missile before or after it has detected and targeted the ship. To defeat an incoming missile

which has detected and targeted the arsenal ship, active defense features can be used. Every system placed on the arsenal ship has associated pros and cons. The pro is its effectiveness to soft kill or hard kill the incoming missile. The cons are the cost of the system and the additional RCS (implying loss of stealth) it adds to the ship.

1. Soft Kill Systems

Passive defense systems are those that reduce detectability or prevent an incoming missile from hitting the ship by means other than physical destruction. Reducing detectability is the same as increasing the effectiveness of stealth. Soft kill is the destruction or confusion of an incoming missiles' sensors or guidance system. This causes the missile to be drawn off target or renders it ineffective to function as designed, thus missing the ship. Electronic counter measures (ECM) and Electronic support measures (ESM) with CHAFF function in this manner.

a. Stealth

Reducing RCS through 'bending' metal from the traditional 90 degree right angles or use of radar absorbing materials; reducing IR through innovative ways of cooling engine exhaust or ship surfaces; reducing visual through camouflage or decreasing the amount of ship above the waterline; reducing acoustic through innovative designs in mechanical systems and sound and vibration control; and reducing EME through employing EMCON tactics are areas the user needs to consider employing on the arsenal ship. Again, for stealth there are pros and cons to be input; effectiveness and cost. Stealth is a survival multiplier. It is well known that reducing a ship's RCS will greatly increase the effectiveness of chaff on an incoming missile. The same applies to IR reduction and TORCH deployment. But the extent of the effectiveness in combat is not known.

The cost of stealthing a ship is relatively unknown. Starting without a base ship design further complicates the problem. If stealth is to be considered as a whole, then the user must aggregate the affects of each signature reduction and their cost. If each system is considered separately, then an estimate of effectiveness and cost is required. In the absence of detailed estimates and to simplify the complication, this thesis will consider that stealthing a 20 thousand ton arsenal ship will have an affect of reducing our notional

stealth signature, RCS, to 1/8 the original RCS for a 20 percent cost increase. Table 9 shows the values as they are input into the model. AAW PK is a multiplier that effectively "destroys" (renders ineffective) seven out of eight ASCMs that would otherwise hit the arsenal ship. The 'additional RCS' input is not a factor, since stealthing a ship does not add more RCS signature to the ship.

Nomenclature	Min Qty	Max Qty	AAW Pk	Procurement	Annual O&S	LifeCycle	Annual Cost	Additional RCS
Stealth	0	1	0.875	$90,000,000	$0	35	$2,571,429	0

Table 9: Stealth values input into the model

b. ESM/CHAFF

ESM provides the ship a 'heads up' of an incoming missile. The system then alerts the ship to the incoming and is able to automatically fire CHAFF/TORCH if it is configured to do so. Evasive maneuvers and seducing missiles with CHAFF or TORCH rounds are methods to draw off an incoming missile.

As discussed in the escort self defense section, this thesis uses 32.5% for the ESM/CHAFF soft kill probability. This figure is considered an underestimation, since Schulte's analysis of ASCM effectiveness in the littoral finds that "Softkill measures employed against anti-ship missiles were extremely successful, seducing or decoying every missile it was used against. In every engagement where a defender was alerted and deployed softkill measures, every missile salvo was entirely defeated" [Ref 5, p. 35]. O&S cost per year is $500K per year (FY95 dollars adjusted to FY96 using 3% inflation rate). This cost is the average of all ESM systems (SLQ-32 V1 - 4). Procurement data for a SLQ-32 V2 and 6 MK36-6 rocket launchers is $4.34M. For additional RCS, we estimated a height of 3 feet for this feature. The values input into the model are given in Table 10.

Nomenclature	Min Qty	Max Qty	AAW Pk	Procurement	Annual O&S	LifeCycle	Annual Cost	Additional RCS
Esm/Srboc	0	1	0.325	$7,025,000	$500,000	35	$700,714	1050

Table 10: ESM/SRBOC model input values

2. Hard Kill Systems

Active defense systems are those that apply physical force to destroy or damage an incoming missile to the extent that it does not hit the ship, or reduces the damage the missile causes (i.e., causes the missile to explode before hitting the ship). These systems

can acquire and attack the incoming missile at the 10-20nm range like the rolling airframe missile (RAM) or evolved sea sparrow (ESS), or at shorter ranges like the CIWS (0-1nm). The 5”54 gun loaded with an IR round also has a small ASCM capability. We did not consider using the 5”54 gun option since it is assumed there will not be enough time to acquire, target, load and fire the gun in a littoral engagement. New advanced systems like Ram accelerator CIWS, improved SMs, etc. can be tested for their overall effects in arsenal ship survivability and battleforce sustainability.

a. RAM

The RAM (RIM-116) series surface-to-air missile is designed to provide defense against cruise missiles. It is a box-type launcher on the outer deck of a ship and is propelled by a modified Sidewinder missile rocket motor, guided by a Stinger missile seeker and carries a Sidewinder warhead. It is a fire and forget missile. In this thesis 0.7 is used as the effectiveness against an incoming target [Ref. 15]. In this case only one system will be considered. Since cost data is not available, it is estimated that the lifecycle cost for RAM would be $10M amortized over 35 years. Annual O&S cost is assumed to be similar to that of CIWS, $378,000. The total annual lifecycle cost is then $661,714. For additional RCS we assume this feature has a total height of 15 feet. Table 11 shows the RAM values used in the model.

Nomenclature	Min Qty	Max Qty	AAW Pk	Procurement	Annual O&S	LifeCycle	Annual Cost	Additional RCS
RAM	0	0	0.7	$10,000,000	$376,000	35	$661,714	5250

Table 11: RAM model input values.

b. ESS

The Evolved Sea Sparrow (ESS) is based upon the current AIM-7M Sea Sparrow missile. It includes improvements in the rocket motor, aerodynamic control system and auto-pilot while remaining a vertically launched missile. This feature allows for the missiles to be stored in the arsenal ships VLS cells, thus reducing top side ‘clutter’. The MK 91 FCS has a dual “headlight” configuration of antennas, one for transmitting and the other for receiving. ESS requires active guidance from the ship. This thesis will use 0.7 as the effectiveness against an incoming target. [Ref. 15]. Since cost data is not available, an $8M is estimated for procurement. O&S costs are assumed similar to that of

ESM/CHAFF, $376,000 per year. The total annual lifecycle cost is then $604,571. For additional RCS, we assume this feature has a height of 10 feet. Table 12 shows the ESS values used in the model.

Nomenclature	Min Qty	Max Qty	AAW Pk	Procurement	Annual O&S	LifeCycle	Annual Cost	Additional RCS
ESS	0	1	0.7	$8,000,000	$376,000	35	$604,571	3500

Table 12: Evolved Sea Sparrow model input values

c. *Vulcan Phalanx CIWS*

The MK 15 Close-in Weapon system is a short range defensive system effective against air targets between (0-1nm). If so equipped, the arsenal ship will contain the required number of CIWS systems to give the ship 360 degree coverage. Each CIWS is a self contained system and is procured and supported as such. Whether there are one, two, three or four mounts on the ship, will be reflected in the cost of the total system. In the model, the quantity for CIWS should be '0' for no CIWS, or '1' for a set of two mounts. The AAW PK for CIWS is 0.575 which is the average effectiveness against four different types of missiles [Ref. 15]. The O&S cost data for two mounts is $752,000 from the Center for Naval Cost Analysis VAMOSC program office [Ref. 16]. Procurement cost is $12,391,400 dollars for two mounts obtained from Data Search Associates [Ref. 12]. The total annual lifecycle cost for two mounts is then $1,106,040. For additional RCS, we assume this feature has a height of 10 feet for each mount. Table 13 shows the CIWS values used in the model.

Nomenclature	Min Qty	Max Qty	AAW Pk	Procurement	Annual O&S	LifeCycle	Annual Cost	Additional RCS
CIWS	0	1	0.575	$12,391,400	$752,000	35	$1,106,040	7000

Table 13: CIWS model input values

C. VULNERABILITY

These are features that reduce vulnerability after a ship has been hit. All features represented in this section will be taken in parallel to combat the incoming missiles. Another way of saying this is that they "will decrease post-hit vulnerability." [Ref. 11]. The features listed in this area are considered to work in parallel to reduce the effects of a hit. Features considered are component redundancy, component location, passive damage suppression, active damage control, component shielding and component elimination. In the case of the arsenal ship this can equate to the following areas:

- Hull girder strengthening
- Blast hardened bulkheads
- Magazine protection/mass detonation protection
- Fully redundant combat systems
- Double ended propulsion
- Ship size

The effect of varying vulnerability features in cruisers and destroyers was explored in a NSWC Carderock study. This study explores increasing survivability by decreasing the ship's vulnerability. The arsenal ship design could benefit from a study like this. The Ship Vulnerability Model (SVM) "which provides probability for loss of ship functions after hits by selected threat classes" could benefit the arsenal ship designers prior to the ship being built. [Ref. 7]

For each feature considered, an effectiveness value (AAW Pk), cost and additional RCS input are required. Since the data in Ref. 7 is classified, the authors have chosen to use an aggregate hardening input. Our hardening package is assumed to provide the arsenal ship with a threefold increase in staying power. The cost is assumed to be 35% of the base ship cost. It is assumed that hardening does not increase the ship's RCS signature. See Table 14 for our model input for hardening.

Nomenclature	Min Qty	Max Qty	AAW Pk	Procurement	Annual O&S	LifeCycle	Annual Cost	Additional RCS
Hardening	0	1	0.6667	$157,500,000	$0	35	$4,500,000	0

Table 14: Hardening model input values

D. SURPRISE ATTACK/NO SURPRISE ATTACK OPTION

If the surprise option is not toggled, then the task force is assumed to be aware of every incoming hostile missile. Toggling surprise attack assumes that the first missile attack will be a surprise and will penetrate the task forces defenses with a probability of 1. The second missile attack is also assumed to be a surprise, but only has a guaranteed penetration of .5. All missile attacks which follow will be subject to a task force which is now alert and defending against incoming missiles at full effectiveness. This option originates from a littoral scenario where the battle space is small and the enemy launches without any indications or warnings. This is a real problem. Our task forces can rarely operate in a status of weapons free. The first indication of hostilities may be a surprise missile launch.

E. AGGREGATE INCREASED DETECTABILITY

If the increase in RCS attributed to each feature placed on the arsenal ship is unknown or the crude approximations presented in this thesis are not considered reasonable, then this option is recommended. Employing this model option assumes that any hard kill or soft kill features placed on the arsenal ship will cut the stealth effectiveness in half. Topside systems increase detectability by creating increased radar return, light, heat and smoke. By how much is difficult to determine, and it is complicated when stealthing is involved, but the effect is probably greater than the increase in RCS. Our simple solution is to activate the "reduced RCS" feature when the arsenal ships defenses are employed.

F. LIMITING THRESHOLDS

These inputs define desired survivability and cost. If both limiting criteria can be met, they system produces feasible solutions. This thesis uses .8 as the survivability criterion and 50 million dollars for the maximum annual system cost.

G. SUSTAINABILITY INPUTS

The inputs for the Sustainability model are identical to the Survivability model's inputs, as shown below.

1. Arsenal Ship Design

The user chooses the arsenal ship's design by hardwiring the desired soft kill, hard kill, and vulnerability features in the Excel spread sheet. The design can be a configuration produced using the Survivability model, or another that the user designates. From our runs of the Survivability program, we have decided to run varying designs of the arsenal ship. The inputs for each run will be discussed in Chapter V.

2. Task Force Composition

The Task Force can contain any number of escorts. The user decides based on the scenario being examined. This can be done by hardwiring the escort minimum and maximum values.

3. Limiting Criteria

In the Sustainability model, the only limiting criterion is the arsenal ship's survivability level. This value is the percentage of staying power above OOA which the user desires the arsenal ship to retain. Once the staying power falls below this threshold, the arsenal ship is considered OOA. Our requirement will be that the arsenal ship remain above 80% of its staying power.

V. SURVIVABILITY SUB-MODEL RESULTS

We do not intend to design the arsenal ship. Chapters V and VI show examples of how the model can be used. We cannot explore all possible configurations as a typical run may yield more than 62,000 possibilities. That is just for our data. Varying parameters and introducing additional systems can increase the candidates manyfold. We present examples that we believe are realistic or interesting and perform sensitivity analysis on significant factors affecting results.

A. DESCRIPTION

Unless otherwise stated, the inputs shown in Table 15 are used in this chapter for running the Survivability Sub-model.

	Escort Ships							
Ship Class	Min Qty	Max Qty	SAM Pk	Procurement	Annual O&S	LifeCycle	Annual Cost	# ASM SAMs
CG-47	0	2	0.7	$1,237,038,179	$28,814,948	30	$70,049,554	70
DDG-51	0	2	0.7	$1,063,900,596	$21,500,976	30	$56,964,329	50
DDG-993	0	1	0.5	$469,262,553	$25,156,840	30	$40,798,925	56
DD-963	0	0	0	$469,262,553	$44,250,516	30	$59,892,601	0
FFG-7	0	2	0.4	$298,513,074	$17,077,516	30	$27,027,952	21
Arsenal Ship	0	0	n/a	$450,000,000	0	35	$12,857,143	284

	Self Def	Underway	Displace	RCS	Mission Time		
Ship Class	Pk	Days	Tons	Value	Value	Notes	Ann. Esc. Cost
CG-47	0.503	90	9600	49896	0.85		$14,681,619
DDG-51	0.503	90	8300	24998	0.85		$11,939,099
DDG-993	0.394	90	9800	51515	0.85		$8,551,008
DD-963	0.394	90	8000	51515	0.85		$12,552,833
FFG-7	0.394	90	3700	33069	0.85		$5,664,763
Arsenal Ship	n/a	n/a	20000	36750			

	Systems							
Nomenclature	Min Qty	Max Qty	AAW Pk	Procurement	Annual O&S	LifeCycle	Annual Cost	Additional RCS
Stealth	1	1	0.875	$90,000,000	$0	35	$2,571,429	0
Esm/Srboc	1	1	0.325	$7,025,000	$500,000	35	$700,714	1050
CIWS	1	1	0.575	$12,391,400	$752,000	35	$1,106,040	7000
ESS	1	1	0.7	$8,000,000	$376,000	35	$604,571	3500
Active Defense Effectiveness	0.55							
Hardening	1	1	0.66666667	$157,500,000	$0	35	$4,500,000	0

Surprise Attack Option

No Surprise Attack

Degrade Stealth by 1/2, thus RCS degradation column rendered in-effective

Nomenclature	Notation	Value
Incoming Missile Shots	M	100
Missile Explosive Weight	He	250
Minimum Survival Probability	MINPROB	0.8
Annual Life Cycle Cost	Cost	$35,000,000

Table 15. Input Parameters for Survivability Example

B. MEASURES OF EFFECTIVENESS APPLIED

The survivability model results reflect the inputs above for a raid of 100 incoming missiles and show three different possible measures of effectiveness (MOEs) one may

employ to determine the best configuration candidates. Direction from higher authorities and the user's preferences will dictate which is best for the situation.

- MOE #1: (Best Cost/Effectiveness ratio) This MOE sorts the output by the Cost/Effectiveness, subject to meeting both cost and survival thresholds — lowest is best.
- MOE #2: (Minimum Cost Subject to Survivability Constraint) This MOE sorts the output in ascending cost order.
- MOE #3: (Maximum Survivability Subject to Cost Constraint) This MOE sorts the output in descending order of survivability.

The output for each MOE is presented graphically in composite charts which show the configuration components in different colors on a bar graph. A line indicating survivability level is superimposed and read from the scale in the right margin. The graphs display the top six configurations for each MOE, first under the input conditions stated above and then for surprise attacks. The contents of Figures 9 through 14 are indexed in Table 16.

FIGURE NUMBER	MOE NUMBER	SURPRISE ATTACK
9	1 - Cost Effectiveness	Yes
10	1 - Cost Effectiveness	No
11	2 - Minimum Cost	Yes
12	2- Minimum Cost	No
13	3 - Maximum Survivability	Yes
14	3 - Maximum Survivability	No

Table 16. Index for Survivability

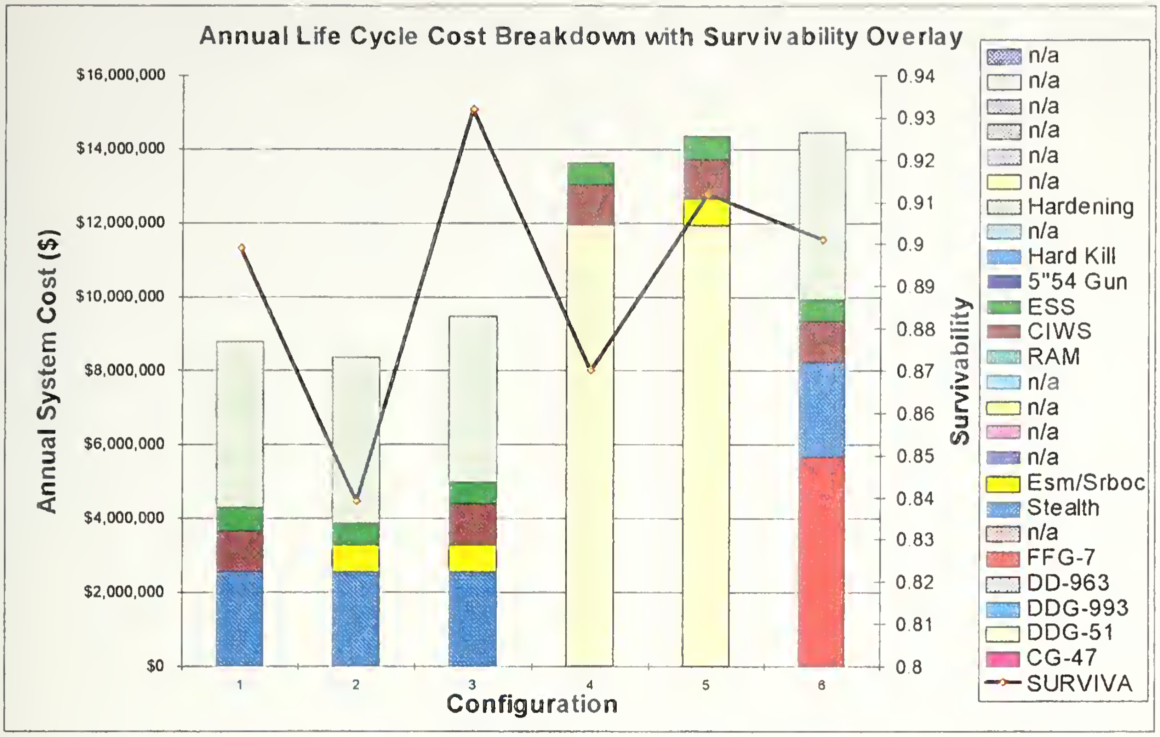


Figure 9. MOE #1: Best Cost/Effectiveness Configurations (No Surprise Attack)

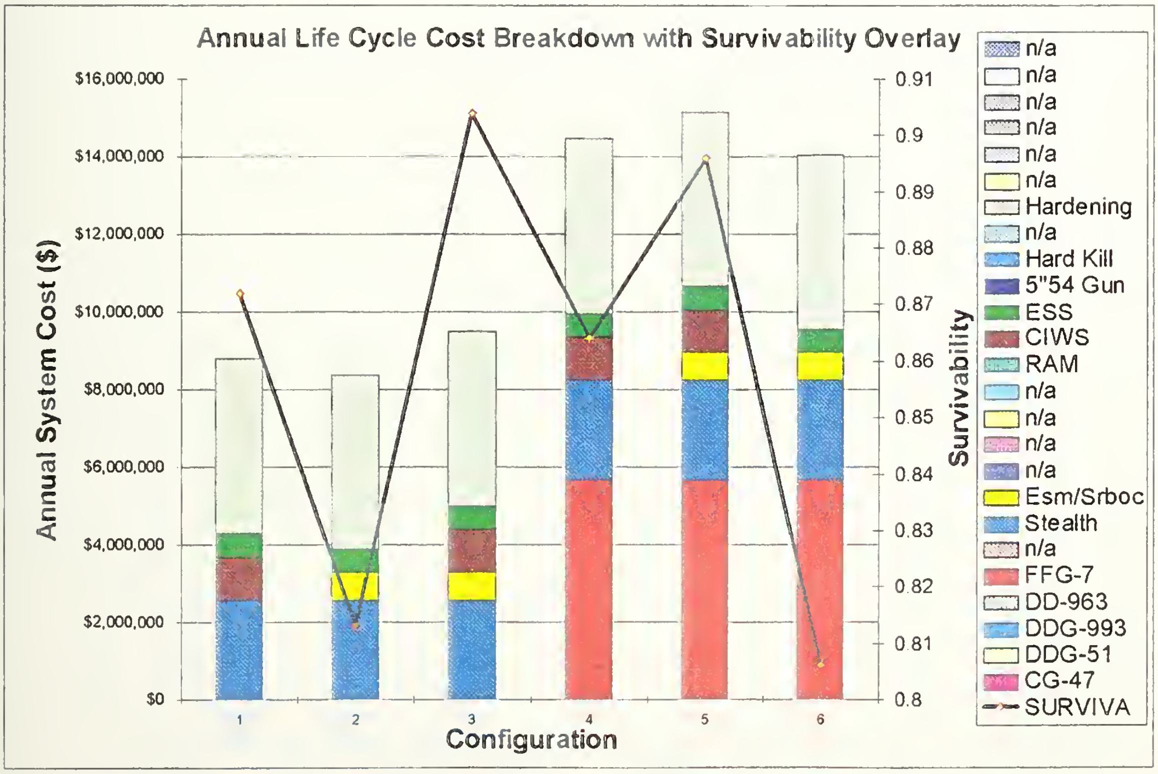


Figure 10. MOE #1: Best Cost/Effectiveness Configurations (Surprise Attack)

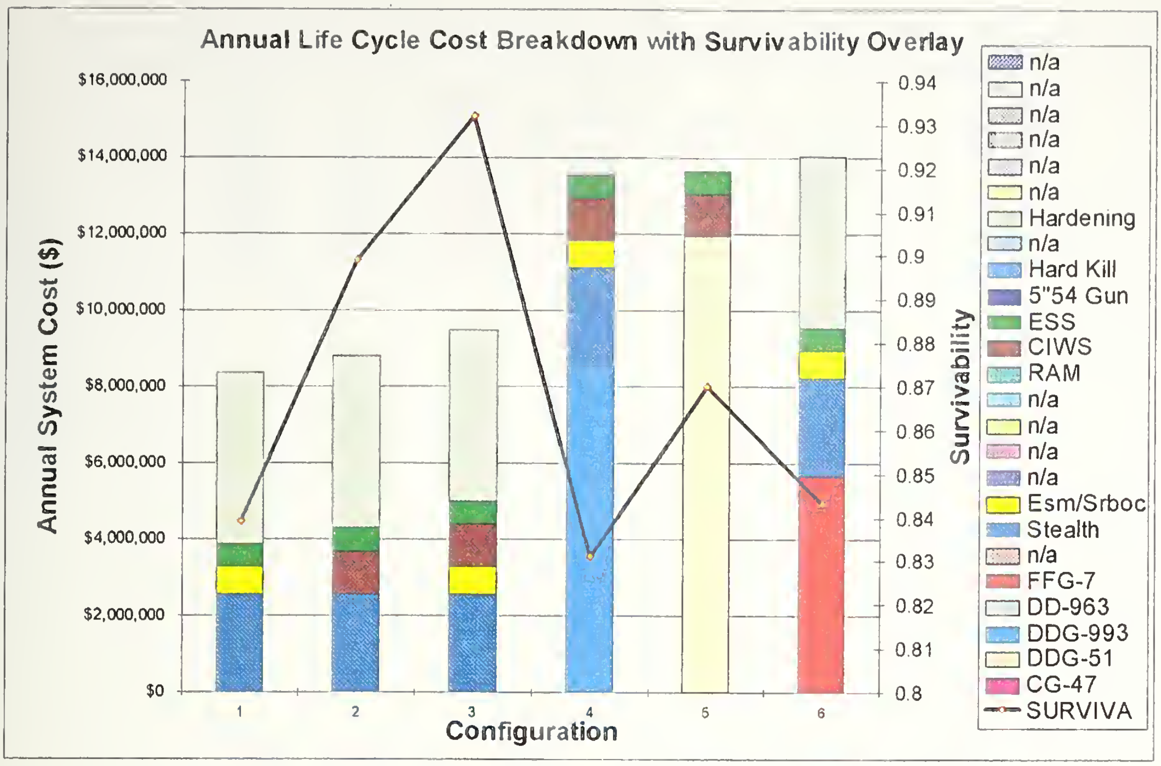


Figure 11. MOE #2: Minimum Cost Configurations (No Surprise)

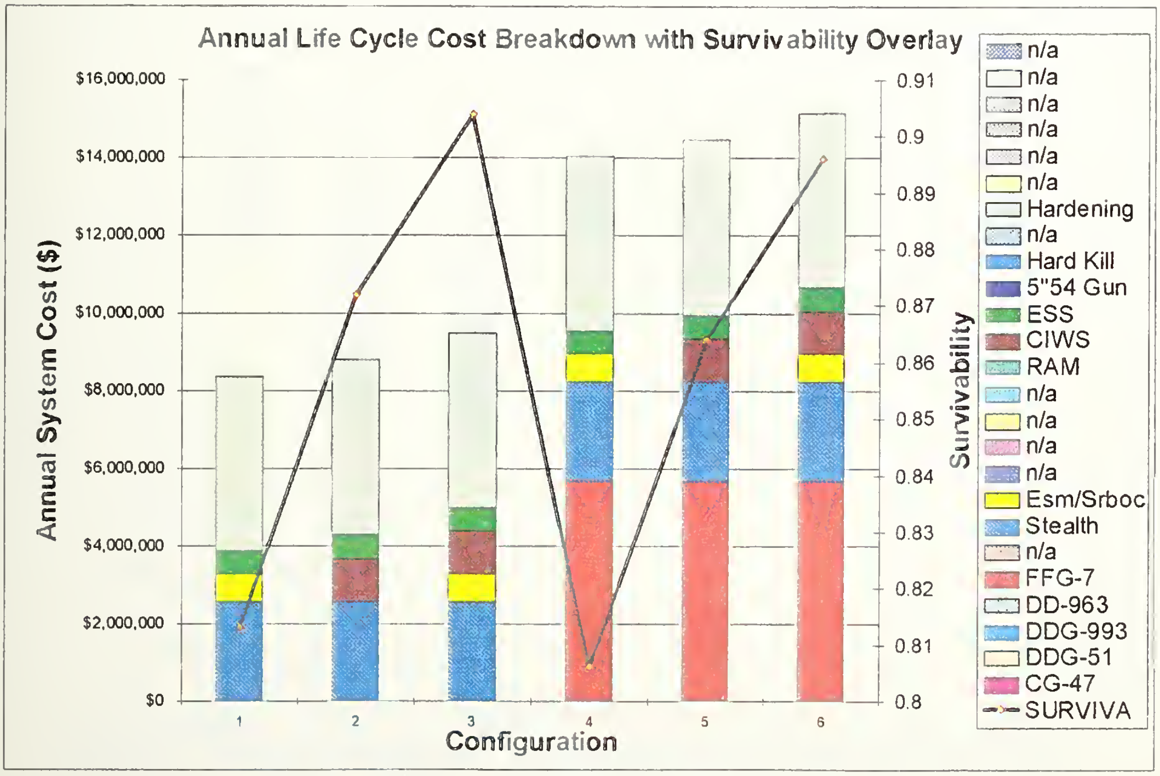


Figure 12. MOE #2: Minimum Cost Configurations (Surprise Attack)

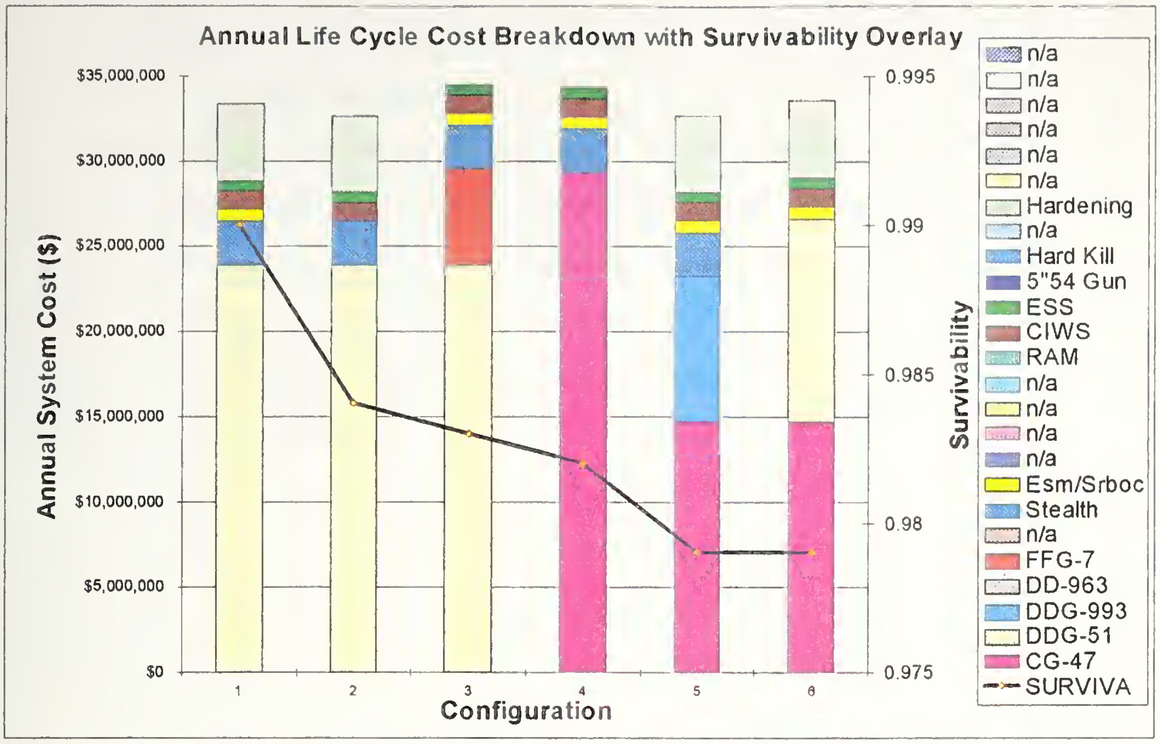


Figure 13. MOE #3: Maximum Survivability Configurations (No Surprise Attack)

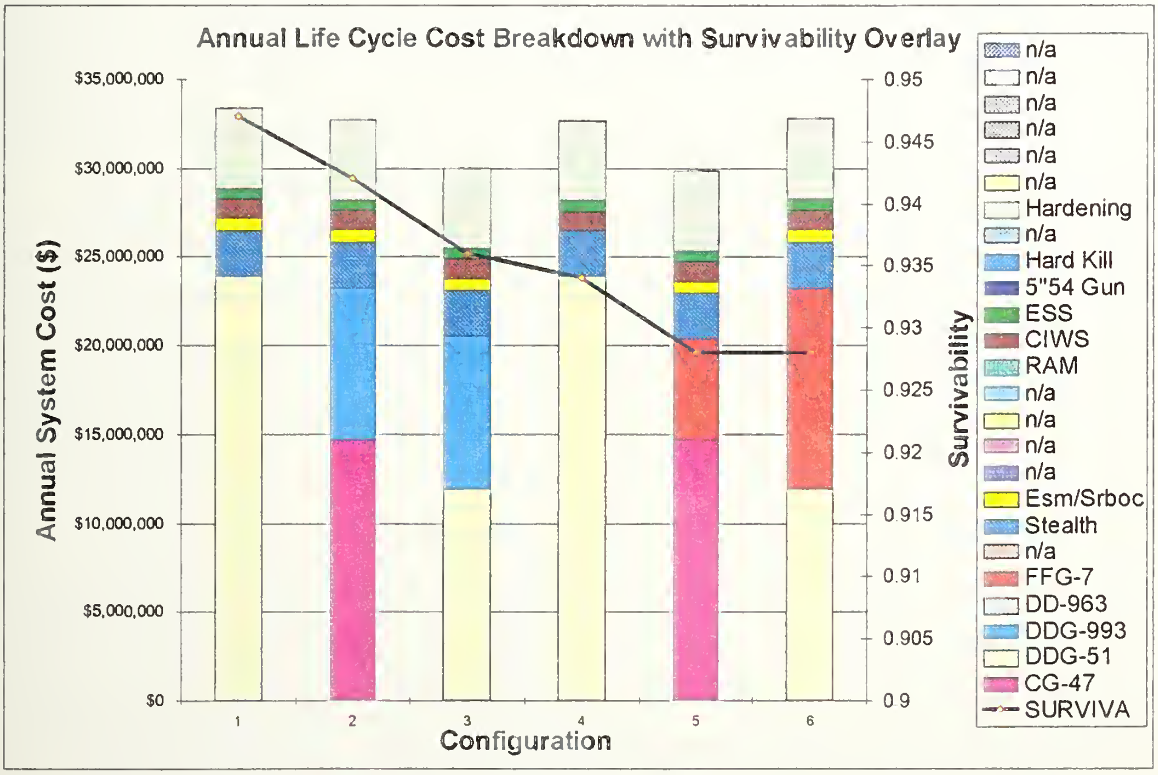


Figure 14. MOE #3: Maximum Survivability Configurations (Surprise Attack)

C. INTERPRETATION OF BEST CONFIGURATION RESULTS

1. No Surprise Attacks

Of the top six configurations for MOE #1, all six included one or more hard kill systems. Four used stealth, and four incorporated hardening. Three included soft kill, and the bottom three employed escorts. For MOE #2, the overall breakdown of desirability of features was nearly the same. In fact, four of the top six configurations are the same for MOE #1 and MOE #2. The order of preference differs, however. Stealth was added in five vice four configurations.

MOE #3 produced drastically different results. All of the top six configurations incorporated escorts and hard kill systems. Soft kill and stealth each appeared in five configurations, and hardening was present in four. Each of the top configurations from MOE #3 cost two to four times the configurations produced in the other MOEs.

2. Surprise Attacks

Recall the assumption that in a surprise attack the first missile will strike a ship and the second will have a fifty percent chance of leaking through defenses and hitting a ship. The impact is a reduction in overall arsenal ship survivability of 2.5 to 5 percentage points. The decline is greatest in configurations with escorting warships.

The astute reader, trying to ascertain patterns may notice an apparent paradox in the interrelationships of adding escorts and changing surprise options. When surprise is not present, adding escorts to a fixed configuration will increase survivability. For a surprise scenario, however, the results seem inconsistent. In some instances adding escorts improves survivability and others not. The illustration below (Figure 15) uses data extracted from Figures 9,10,13 and 14 to demonstrate the issue.

The result is counterintuitive at first. The reason is complex. In Case 1 of the illustration (Figure 15), when a surprise raid is launched on the arsenal ship escorted with an FFG-7, the arsenal ship fares worse than if it operated alone. This is because even though it incorporates stealth, the arsenal ship is more visible when operating with another ship. Making matters worse, there is only one other ship to share the damage inflicted by leakers, and a frigate is relatively small. If the frigate were larger, it would have more

have more staying power and attract a larger share of the leakers. The defense afforded by the frigate is not sufficient to overcome these detractors to arsenal ship survivability. In contrast, the CG-47 and DDG-993 (in case 2 of Figure 15) have sufficient staying power and defensive capability to boost the arsenal ship's survivability even though the effectiveness of the arsenal ship's stealth is affected by operating with escorts.

Case 1:

Survivability

	Base 1	Base 1 +
No Surprise	0.899	0.901
Surprise	0.872	0.864

Case 2:

Survivability

	Base 2	Base 2 +
No Surprise	0.932	0.979
Surprise	0.904	0.942

Base 1: stealth, CIWS, ESS, hardening
Base 1 +: Base 1 and 1 FFG-7

Base 2: stealth, CIWS, ESS, hardening, ESM
Base 2 +: Base 2, 1 CG-47, and 1 DDG-993

Figure 15. Arsenal Ship Survivability Paradox Illustration

3. Generalizations

While each MOE is quite different in emphasis, some configuration recommendations apply universally. Hard kill systems appear in the top six configurations of each MOE regardless of surprise attack. When surprise attack applies, all top configurations incorporate stealth and hardening also.

D. SENSITIVITY

1. Stealth

Since stealth appears in most favorable output configurations, a closer look at the effects of stealth on survivability is in order. Figure 16 shows the effects of stealth for incoming missile raids of size 50, 100, and 150. The configuration includes stealth, ESM, ESS, CIWS, and hardening. The stealth factor ranges from 1 to 12 corresponding with no reduction up to a $^1/_{12}$ reduction in signature. Interestingly, the effects nearly level-off after a reduction factor of about four for the cases studied. This indicates that

while stealth is important, investing past this point provides diminishing marginal returns and may not be the wisest investment.

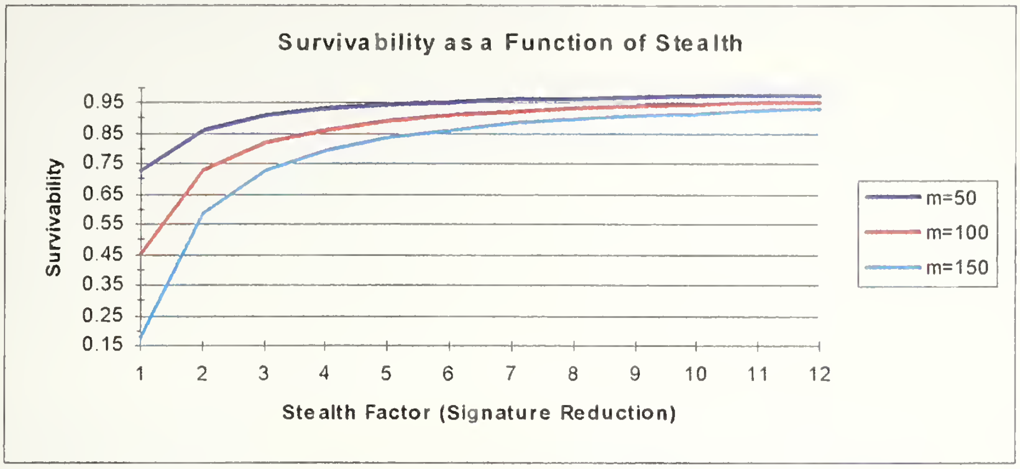


Figure 16. Sensitivity of Survivability to the Degree of Stealth

2. Hardening

Hardening also appears in the best configurations. To test the sensitivity of survivability to hardening, the degree of hardening is varied for a ship with stealth, ESM, ESS, CIWS, and hardening. The hardness factor was varied from one to six and one-half; this corresponds with no improvement of staying power over the base ship up to a six and one-half-fold improvement. The results appear in Figure 17. Again one sees a "knee" in the curve (in the neighborhood of a hardening factor of 3), thus indicating that investments in hardening are good to a point. After that, investments in other systems most-likely will affect survivability more.

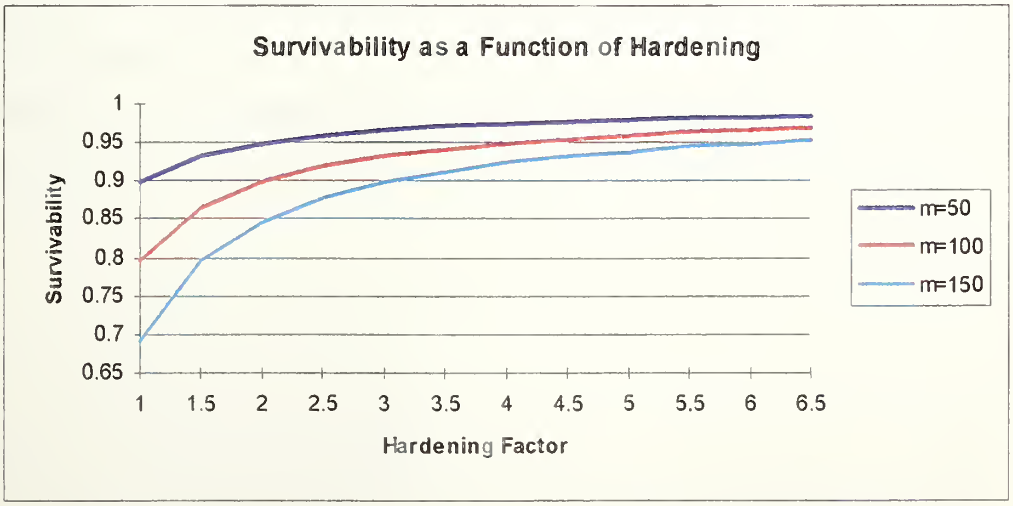


Figure 17. Sensitivity of Survivability to Degree of Hardening

3. Escort Ships

Table 17 summarizes the effects on the arsenal ship's survivability of adding one or two escorts of a particular class to the task force. Three configurations of arsenal ships are examined. The base case incorporates no defensive systems or design features; the next case includes only the ship design features of stealth and hardening; and the final case combines stealth, hardening, CIWS, ESS, and ESM. The survivability (S_A) values are generated from the model, and the values in parenthesis are the absolute increase in survivability over the unescorted case for each configuration. Figures 18 and 19 plot the data for the last two configurations.

Arsenal Ship Configuration	S_A without Escorts	S_A with one FFG-7	S_A with two FFG-7s	S_A with one DDG-51	S_A with two DDG-51s	S_A with one CG-47	S_A with two CG-47s
Base: No Defensive Systems	0 (0)	0 (0)	0 (0)	0 (0)	.191 (.191)	0 (0)	.435 (.435)
Base + Stealth + Hardening	.206	.229 (.023)	.237 (.031)	.389 (.183)	.583 (.377)	.474 (.268)	.751 (.545)
Strong Defensive Systems	.932	.933 (.001)	.934 (.002)	.946 (.014)	.962 (.030)	.953 (.021)	.977 (.045)

Table 17. Effects of Adding Escorts on Arsenal Ship Survivability (S_A)

An arsenal ship without any defensive systems is not survivable with less than two Aegis ships. A ship configured with only modest self-defense features benefits greatly from additional escorts. Both the systems on the escort and the fact that the escorts have larger signatures to draw missiles work to bolster arsenal ship survivability. An arsenal ship configured with formidable self-defense systems will naturally achieve the highest level of survivability when escorted over any other configuration. The marginal increase to survivability from adding an escort is much lower though.

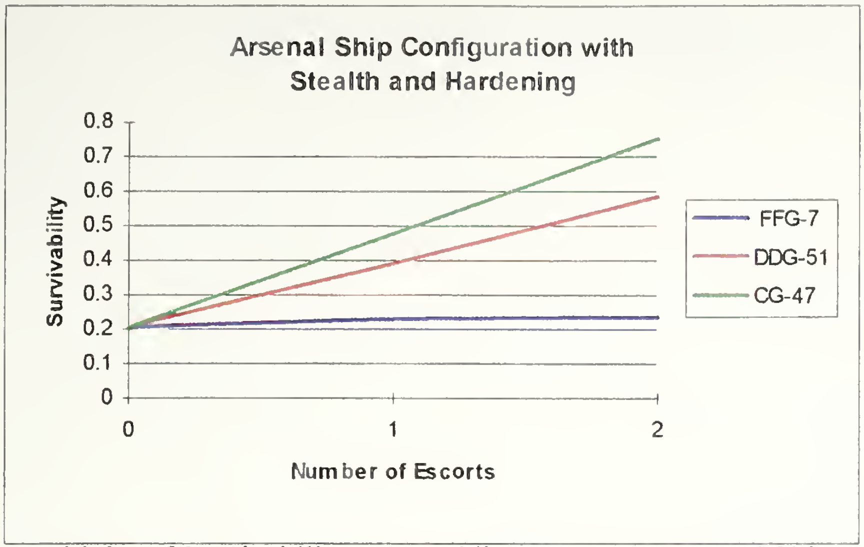


Figure 18. Sensitivity of Survivability to an Adding Escorts to Arsenal Ship with Stealth and Hardening only.

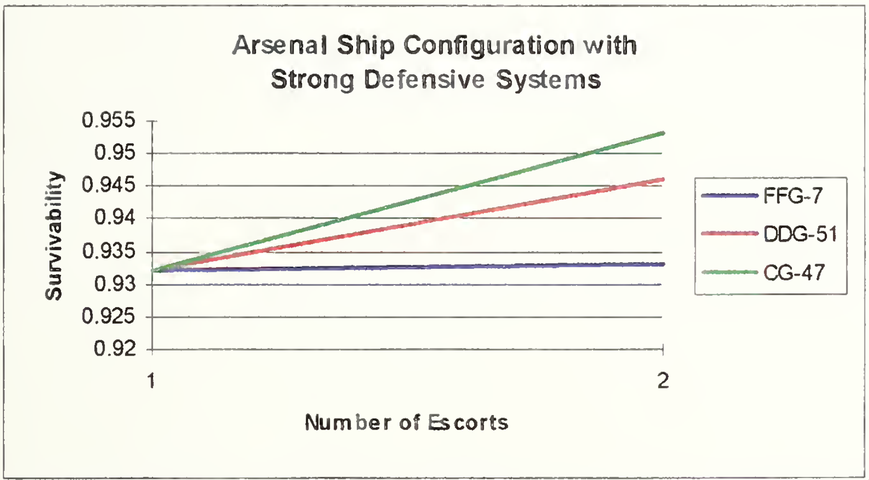


Figure 19. Sensitivity of Survivability to Adding Escorts to an Arsenal Ship with Strong Defensive Systems.

VI. SUSTAINABILITY ANALYSIS

A. DESCRIPTION

Sustainability is measured by the naval component's time on station. It needs to be emphasized that sustainability involves more than a BG's ability to conduct strikes and take hits. These are the indicators of sustainability. A naval component's sustainability results from both onboard ship design and external logistics support (fuel, ordnance, material, food, etc.). In this analysis we will review the impact of an arsenal ship's design and ordnance load on the BG's sustainability. Three areas of sustainability are examined.

- The effect of varying arsenal ship survivability on the naval component's sustainability
- BG sustainability with an arsenal ship vs. with five Arleigh Burkes
- VLS replenishment issues

B. ARSENAL SHIP SURVIVABILITY VS. NAVAL COMPONENT SUSTAINABILITY

The term "naval component" is emphasized because we are not measuring just the sustainability of the arsenal ship. Our approach assumes the naval component's sustainability is equivalent to the escorts' sustainability. We base this on the premise that a BG can remain on station without an arsenal ship, but an arsenal ship cannot remain on station without an escort present, since there are also surface and sub-surface threats which the arsenal ship requires escorts to protect against.

Our approach is to vary the arsenal ship's survivability and examine the impact on the BG's sustainability. Our baseline BG has 1 Ticonderoga Class Cruiser, 2 Arleigh Burke Class destroyers, 1 Kidd Class destroyer and 2 Oliver Hazard Perry Class frigates. This is considered the base case. Table 18 lists each modification to the base that we examine. System 1 is the base and systems 2 through 15 add an arsenal ship with varying degrees of defensive features. Running each system through the Sustainability model with an arsenal ship's limiting survivability of .8, and no surprise attack gives the results in Table 19.

System	BG Composition
1	BG
2	BG, ST
3	BG, SK
4	BG, HK
5	BG, Hard
6	BG, ST, SK
7	BG, ST, HK
8	BG, ST, Hard
9	BG, SK, Hard
10	BG, HK, Hard
11	BG, SK, HK
12	BG, SK, HK, Hard
13	BG, ST, SK, Hard
14	BG, ST, HK, Hard
15	BG, ST, SK, HK, Hard

Key
BG = 1 CG-47, 2 DDG-51 1 DDG-993, 2 FFG-7
ST = Stealth
SK = Soft Kill = ESM/SRBOC
HK = Hard Kill = CIWS, ESS
Hard = Hardening

Table 18: Sustainability Model Run Battle Group Composition

System	Missiles Escorts OOA	Missiles AS OOA	Missiles left on Arsenal	Annual Cost of Arsenal	Annual Cost with Escorts	(lower better) Cost Effect
1	108	111	0	$0	$58,440,350	0
2	176	182	150	$2,571,428	$61,011,778	14610
3	120	109	188	$700,714	$59,141,064	5839
4	210	216	94	$1,710,611	$60,150,961	8146
5	192	187	94	$4,500,000	$62,940,350	23438
6	176	186	150	$3,272,143	$61,712,493	18592
7	180	239	142	$4,282,040	$62,722,390	23789
8	176	199	150	$7,071,428	$65,511,778	40179
9	210	211	94	$5,200,714	$63,641,064	24765
10	210	232	94	$6,210,611	$64,650,961	29574
11	210	220	94	$2,411,325	$60,851,675	11483
12	210	244	94	$6,911,325	$65,351,675	32911
13	180	271	142	$4,982,754	$63,423,104	27682
14	180	371	142	$8,782,040	$67,222,390	48789
15	180	466	142	$9,482,754	$67,923,104	52682

Table 19: Model Results for the Systems identified in Table 1, an arsenal ship limiting survivability of .8, no surprise option and aggregate RCS feature

Table 19 contains the following data. 'Missiles Escorts OOA' is the number of incoming missiles it took to put the escorts OOA. 'Missiles AS OOA' is the number of incoming missiles it took to put the arsenal ship OOA with .8 probability. 'Missiles left on Arsenal' is the number of SAMs remaining on the arsenal ship when it was rendered OOA. 'Annual cost of Arsenal' is the annual system cost above the base arsenal ship cost (for which we assumed $450 million). 'Annual cost with Escorts' is the annual system cost

plus the annual cost of the escorts. The 'Cost Effect' column is the annual cost of the arsenal ship divided by the number of missiles it took to put the arsenal ship OOA.

1. Measures of Effectiveness

The number of incoming missiles required to put the escorts OOA is the measure of effectiveness. The number of incoming missiles equates to 'time on station' if the incoming rate (missiles per unit time) is known. The naval component's data in Table 19 indicates systems 4, 9, 10, 11 and 12 have the greatest sustainability levels. Artificially discrete sustainability levels are introduced as a result of using the "aggregate RCS" degradation factor (refer to Chapter 4.E). The hard kill feature occurred most frequently, being in four of the five systems. Hardening and soft kill features occurred in three of the five systems each.

Stealth is not a feature in any of the five systems with the greatest sustainability. This is an artifact of allocating leakers based on a fair share of the BG's total RCS. The stealthier the arsenal ship, the lower its 'fair share' of leakers, which causes the escorts to be attrited faster, thereby reducing the naval component's overall sustainability. At this point we need to define the term balanced force. A balanced force is a BG whose ships' signature levels are roughly equivalent. It is not practical to expect all ships to have the same signature levels; however as the variance approaches zero, the missiles are allocated more uniformly (allocation per ship = 1/number of ships). With this in mind, as the Navy builds the SC-21 and future ships with lower signatures, the BG's overall signature will decline. Since a balanced force will have the greatest overall sustainability, stealthing the arsenal ship will be essential.

To discern which of these five candidates (4, 9, 10, 11, or 12) is the best, requires further evaluation of the BG's performance under additional criteria.

a. Choice by Arsenal Ship Sustainability

If we choose which of the five systems is best based on greatest arsenal ship sustainability, then systems 10 and 12 are best. In the case of system 12, another way of stating it is that the arsenal ship survives until missile 244, and so system 12 had more staying power remaining when the escorts in the other configurations were put OOA.

Though stealth is not incorporated in any of the systems of choice, the effect of stealth requires explanation in order to interpret the other system results in Table 19. After the escorts are put OOA, two methods are used to attrite an arsenal ship without escorts. When stealth <u>is not</u> a feature, every missile targets the arsenal ship and is subject to its point defense systems. If the arsenal ship is stealthed, the incoming missiles are reduced by the inverse of the stealth factor (1/Stealth Factor) initially. For example, a stealth factor of eight prevents seven out of eight shots from acquiring the arsenal ship. This is why systems 13, 14, and 15 require such a large number missiles to put the arsenal ship OOA.

b. Choice by Ordnance Available

Another way to determine which of systems 4, 9, 10, 11 and 12 is the best can be based on the number of arsenal ship SAMs used. Vice Admiral (Ret.) Joseph Metcalf, one of the Surface Warfare Community's former leaders, espoused that the primary mission of a surface combatant is to deliver "maximum ordnance on target." [Ref. 17, p. 36] He referred to strike ordnance, not defensive ordnance like SAMs. The more strike weapons the BG has, the greater its offensive potential, provided it can survive. In Table 19, all five systems have 94 SAMs remaining after the escorts are put OOA. As a reminder, our arsenal ship has a load out of 228 strike weapons and 284 SAMs (refer to Chapter 4.B.3 for details). Since no escorts remain to control the 94 remaining SAMs, their potential is never realized. Assume, for a moment, that all 228 strike weapons were fired from the arsenal ship and 94 SAMs remained in their cells when it had to leave station. For each of the five systems with 94 remaining SAMs, the load out could be modified to be filled with strike ordnance. This would give the arsenal ship the striking potential of 228 + 94 = 322 strike weapons vice 228. Since "ordnance on target" is the goal, all five systems chosen perform equally well.

c. Choice by Cost

Assuming for a moment that the cost of defending the arsenal ship with a BG is a sunk cost, then screening our five chosen systems by the Cost data in Table 19, indicates that systems 4 and 11 with annual lifecycle costs of $1.7 and $2.4 million, are

best. System 4 incorporates hard kill features and system 11 incorporates hard and soft kill features. Systems 9, 10 and 12 contain hardening which increases their annual cost two to three times higher.

d. Choice by Cost Effectiveness

Another measure is cost effectiveness, which represent the cost for each unit of sustainability. The cost effectiveness column (far right) in Table 19 is calculated by taking the annual life cycle cost without escorts divided by the number of missiles to put the escorts OOA. Since a lower cost effectiveness is desired, systems 4 and 11 are the best with $8,146 and $11,483 per incoming missile respectively. Again, system 4 contains hard kill systems only, and system 11 contains hard and soft kill systems. These systems yield the best "bang for the buck."

2. Interpretation of Best Configuration Results

At this point in the analysis, caution must be taken. The means by which the best of the five is chosen is subjective. If concerned with budget, opt for the lowest cost. Another approach is to choose best "bang for the buck." Looking at individual measures separately can lead to a misinterpretation of the overall analysis. All MOEs need to be examined simultaneously, but each MOE is not necessarily equal in weight, and any weighting scheme we set can easily be countered by another. So, our stand is to rationalize the needs of the warfighter, the CINC. In order to fight and win, a BG must remain on station and overcome the enemy. This implies fighting hurt and delivering ordnance. Of the best systems (4, 9, 10, 11 and 12), systems 10 and 12 provide the BG, as a whole, with the most sustainability, and yield a potential 228 + 94 = 322 cells for missions other than BG defense. From the warfighter's perspective, first and foremost, sustainability is staying power, and systems 4, 9, 10, 11 and 12 are equal. When considering ordnance, all five systems are equal. However, when looking at the BG's sustainability as a whole (not just at the escorts) we see that system 10 affords the most overall sustainability. It is ranked 10 out of 15 for its cost and cost effectiveness, however.

C. SUSTAINABILITY WITH ARSENAL SHIP VS. FIVE ARLEIGH BURKES

In order to deploy the same capacity as the arsenal ship's 512 VLS cells in theater, the Navy would need to deploy 5.7 (or 5 by rounding down to keep costs conservative) Arleigh Burkes. Running the sustainability sub-model for a BG with an arsenal ship and for a BG with five additional Arleigh Burkes, produces the results in Table 20. We chose the arsenal ship configuration which produced the most sustainable BG in Part B of this chapter (system 12). The arsenal ship has soft kill, hard kill, and hardening features, but no stealth. The cost data for one arsenal ship and five Burkes is shown in Table 21.

Category	Arsenal Ship	5 Arleigh Burkes
BG Sustainabiltiy (incoming missiles)	210	233
Potential Strike VLS Cells	228 + 94 = 322	5(40) = 200

Table 20: Sustainability Sub-Model Results for an Arsenal Ship BG and an Arleigh Burke BG. The arsenal ship's minimum survivability criteria is .8; the base BG has 1 CG-47, 2 DDG-51, 1 DDG-993 and 2 FFG-7; and a no surprise scenario was chosen.

The BG survivability levels in Table 20 indicate that the Burke BG can stay on station 10 percent longer than the arsenal ship BG. The runs indicate that the escorts in the arsenal ship BG realize their full potential, by defending the BG until placed OOA. In the Burke BG the escorts become combat ineffective by depleting their SAMs. This means their full staying power is never realized.

The runs indicate that the arsenal ship has 94 SAMs remaining when placed OOA. By replacing these with strike weapons in the load-out, the arsenal ship has a potential strike capacity of 322, while still maintaining the BG's sustainability at 210 missiles. Refer to Table 20. Conversely, the Burkes deplete all their SAMs indicating they could increase the BG's sustainability if more SAMs were available. Reallocating any of the SAM VLS cells on the Burkes would decrease the sustainability of the BG.

The cost values in the "5 Arleigh Burkes" column of Table 4 are derived using the Burke's procurement cost and O&S costs over 35 years. The arsenal ship's costs are unknown, so the following approach was taken for each area category of Table 21. Procurement cost is assumed $450 million (refer to Chapter 2.C.). Added systems cost is the sum of procurement and O&S costs times 35 years for all arsenal ship features. Personnel cost was derived by prorating the personnel cost of an Arleigh Burke by the

crew size of an arsenal ship (assumed 50) multiplied by 35 years. Material cost for an arsenal ship is assumed to be equal to that of a single Arleigh Burke for 35 years. The depot cost is assumed to be equivalent to a single Ticonderoga cruiser for 35 years. [Ref. 13, Ref. 16]

Category	Arsenal Ship	5 Arleigh Burkes
Procurement	$450,000,000	$5,319,502,980
Added Systems Cost	$241,896,375	$0
Personnel Costs	$48,383,314	$1,616,002,675
Material (POL, Repair)	$253,296,120	$1,266,480,600
Total Cost	$993,575,809	$8,201,986,255
Number of Missiles	512	450
Cost per Missile	$1,940,578	$18,226,636

Table 21: Cost Comparison of an Arsenal Ship vs. Five Arleigh Burke ships in a BG

A quick comparison on the cost data in Table 21 shows that five Burkes cost 11.8 times more than an arsenal ship. The Burkes cost 9.4 times more per missile than the arsenal ship.

D. VLS REPLENISHMENT ISSUES

An arsenal ship with 512 cells is a mixed blessing. It will provide a task force with 512 more missiles in theater, thus increasing sustainability of forces on station. However, VLS replenishment at sea is still a problem, and pier side replenishment time is substantial. To put this in perspective, 512 cells with a reload rate of 5 minutes per cell (highly optimistic) would take approximately 43 continuous hours to reload. As it stands now, an Aegis ship takes 2-3 days to reload about 100 VLS cells, so it would take 10-15 days to reload an arsenal ship with 512 VLS cells. Replenishment is the Achilles' heel in VLS operations. An article published in the Fall 1988 UNREP Journal stated:

> "In wartime the enemy decides when and where we expend defensive ammo, so an ammo UNREP may be needed any time, even when the seas are rough or the decks are icy. While we may be able to rearm our aircraft carriers under these conditions, our ability to handle missiles in dollies or in VLS canisters on cruisers, destroyers, and frigates is currently extremely poor." [Ref. 18]

Our ability to UNREP VLS missiles at sea has not improved much since the article was written. The following example illustrates the potential dilemma. Our base BG

without an arsenal ship encounters 25 incoming missiles, at which time the first Burke requires replenishment. If operating in the Sea of Japan it would take approximately 29 hours at 28 knots to reach Sasebo, 6 hours to reload 65 cells (assuming reload rate of 5 minutes per missile and a demand of 50 SAMs and 15 strike weapons), and another 29 hours to get back on station. This equates to 2.8 days off-station. For a multi-mission platform like the DDG-51 or CG-47, this is magnified.

It is frequently predicted that future warfare will be intense in the early days of an MRC, with the tempo leveling off after around the 10th day of conflict [Ref. 10]. If this is the case, even three days off station for our multi-mission platforms will severely reduce the sustainability of the naval component in theater. The arsenal ship provides a strong but temporary fix to the VLS replenishment problem that results from a limited number of missiles on the DDG-51 and CG-47. The arsenal ships will surely fill the gap needed for the surge in requirements at the start of a conflict. Once its missiles are expended, however, the arsenal ship will be away for a long time. It is optimistic to assume the ship can transit at 20 knots a great distance (escorted, of course), reload and return in 15-20 days, that forward logistics bases will be capable of reloading VLS quickly, and that the ordnance will be available. At today's production rate (100-120 Tomahawks per year) it could easily take two or more years worth of production to refill one arsenal ship. With so many VLS cells on the cruisers, destroyers and six arsenal ships we're looking at most missiles being at sea, and very few in reserve for replenishment.

VII. CONCLUSION

A. SUMMARY

The development of an arsenal ship represents fundamental change in naval and joint warfare. Such a vessel will operate in the littoral and be able to provide strikes ashore and theater ballistic missile defense. Additionally, weapons not previously placed on naval ships can occupy VLS cells and provide new forms of direct support for ground troops. The added capabilities, however, come at the cost of exposing the ship to sudden and potentially numerous, technologically advanced, sea and land-based missile attacks.

Our Arsenal Ship Tradeoff Analysis Model consists of a survivability and a sustainability sub-model. The survivability sub-model is a tool that may aid in the design of the ship by predicting how the ship will survive against a specified threat depending on the hard kill, soft kill, stealth, and hardening features built-in and the sevices provided by escorting surface combatants (SCs). The sustainability model considers weapon logistics and may prove useful in determining what portion of the arsenal ship's VLS cells may be devoted to offensive weapons.

B. CONCLUSIONS

Based on exercising the Tradeoff Analysis Model with reasonable weapon system effectiveness values, cost estimates, and three different measures of effectiveness, we advocate an arsenal ship design that balances offense and survivability, the likes of which have not been seen in U.S. warship design since World War II.

Justification of this conclusion is involved. The analytical basis is explained in detail on pages 42 to 48 of Chapter 5. The rationale can be summarized as follows:

- We premise that combatants operating in littoral waters will be subject to increasingly dense and sophisticated missile attacks. Among them, surprise attacks will occur.
- To carry out the multiple missions envisioned for it, the arsenal ship will be exposed to such attacks. It can be escorted intermittently and only when required, thereby saving the cost of built-in survivability. What fraction of the

cost of the escorting surface combatant to charge against the arsenal ship is crucial and depends on the proportionate time taken from other surface combatant tasks. The dollar value is nearly impossible to determine analytically. The multi-mission combatant escort cannot be regarded a free good (on the basis that no added SCs are purchased as arsenal ship escorts) because the SC may be lost in protecting the arsenal ship, in which case it is gone from every other mission, too.

- Fortunately, for a wide range of circumstances and measures of effectiveness, the analysis shows that building survivability into the arsenal ship is almost always preferred to assigning escorts, even when only a small fraction (18.6%) of the SC's life cycle cost is charged against the escort role.
- The preference for and selection of a survivability feature is less easily described. The incorporation of stealth characteristics is, by the analysis, the feature appearing in preferred designs most often. This may be a consequence of the numbers chosen. The reader is cautioned to examine the numbers in detail but is also warned that alternative numbers will be difficult to find. In particular, the reader's attention is invited to Figure 16, page 48, which strongly supports a moderate investment in stealth.
- We have gone to some pains to show that stealth, ship hardening, and defensive short range, hard and soft kill systems are complementary. For example, stealth adds nothing when the arsenal ship is firing a large missile volley, radiating, subject to air attack with bombs, surface gunfire attack, or a submarine launched torpedo attack. But, hardening retains its effectiveness in all these circumstances.
- Our overall conclusion is that stealth, ship hardening, and some set of modern point defense (hard and soft) are, in view of their modest cost in construction and operating personnel, well worth the modest cost on the margin because the arsenal ship's concept of operation requires that it be exposed to major attack.

- Further, until the arsenal ship has expended its massive offensive punch, there will be circumstances in which it should be escorted. It will probably draw the attacks by the enemy to itself in the way CVs do.
- The arsenal ship alleviates the requirement to frequently cycle SCs with fewer VLS cells from the scene of action off station to a replenishment site and back again into the action. By its presence, the arsenal ship will sustain other SCs on station. It can remain on station longer than any other ship for a given missile delivery rate, but when its weapons are expended the reload problem will take it off station for a considerable amount of time.

C. RECOMMENDATIONS

Our recommendation for arsenal ship survivability features is to incorporate stealth, point self-defense systems, and hardening into the design.

Even though hard kill systems were more commonly seen in the analytically preferred results than soft kill systems, we believe soft kill systems are essential for littoral operations. First, soft kill is synergistic with stealth and softkill effectiveness is amplified. Second, as noted, the Schulte thesis concluded that soft kill measures have been highly effective in actual combat, but hard kill systems remain largely unproven [Ref. 5]. Operating in littoral waters with current rules of engagement (weapons not free) makes the arsenal ship vulnerable to initial and sudden attacks without ample time to respond with hard kill.

Our model shows that when surprise attacks occur, hardening is a very attractive feature of ship design. The additional staying power to remain mission capable after at least one hit will help ensure that the arsenal ship's 500-plus missiles are not rendered useless by a lucky or cheap shot.

A balanced design will seek to maximize the arsenal ship's net delivered firepower over the combat life of the ship. Incorporating *all features* listed is, according to the analysis, tantamount to over-designing arsenal ship survival features, when its survival *with those features* is compared to the survival of the accompanying present-day surface combatants. Since the DDG-51 and CG-47 cost roughly the same to procure as an arsenal

ship-plus-missile load-out, and they will be less survivable, this may appear out of balance. However, in the future as more Arleigh Burke destroyers and SC-21 type warships enter the fleet, matching stealth and superior hardness will provide operational balance.

D. AREAS FOR FURTHER STUDY

Our thesis concentrated on the ASCM threat to the arsenal ship. While this is most likely the predominant danger, other nemeses such as submarine and mine threats should be explored. Currently ships are not designed to withstand under hull blasts from mines or torpedoes. Hardening ships displacing 10,000 tons or less against these threats is not feasible, but if the arsenal ship is in the range of 20,000 tons, then a tradeoff analysis is possible between the choices of ASW screening, active countermeasures, and hull hardening. [Ref. 7]

We studied the sustainability of the naval component only. Since the arsenal ship is a joint war fighting platform that through CEC can be utilized by ground troops as well, a theater level study of the marginal value of the arsenal ship's contribution to the ground war is in order, with emphasis on the critical events at the war's onset. With over 500 VLS cells, the ship will surely contribute to checking the enemy onslaught by threatening a massed surge or pulse of power delivered in a short time. The service performed will encompass not only destroying hardware but promoting caution and slowing down the enemy's operations as he exercises deception, concealment, and prudent behavior in general.

Currently the Navy's capability to conduct underway replenishment of VLS cells is inconsequential. VLS cells are here to stay, with a growing variety of weapons. Faster replenishment methods, be they at sea or ashore, beg for technological development.

APPENDIX A. ABBREVIATIONS AND ACRONYMS

A/C - aircraft

ARG - amphibious readiness group

ASCM - anti-ship cruise missile

ASW - anti-submarine warfare

ATACMS - army tactical missile system

BAT - battery

BDE - brigade

BN - battalion

C4I - command, control, communications, computers, and information

CEC - cooperative engagement capability

CG - cruiser

CIWS - close-in weapon system

CINC - Commander-in-Chief

CMD - command

CNO - Chief of Naval Operations

CVBG - carrier battle group

DARPA - Defense Advanced Research Projects Agency

DD - destroyer

DDG - guided missile destroyer

ECM - electronic countermeasures

EME - electromagnetic emissions

EMCOM - emissions control

ESM - electronic surveillance measures

ESS - evolved sea sparrow

EW - electronic warfare

FCS - fire control system

FFG - guided missile frigate

FY - fiscal year

IR - infrared

MRC - major regional contingency

NSWC - Naval Surface Warfare Center

O&S - operations and support

OOA - out of action

OMG - operational maneuver group

OP - operation

OTH - over the horizon

PD - point defense

PK - probability of kill

PR - program review

PSSK - single salvo kill probability

RAM - rolling airframe missile

RCS - radar cross-section

RDT&E - research, development, testing, and evaluation

SAM - surface to air missile

SC - surface combatant

SLAM - stand-off land attack missile

SRBOC - super rocket blooming chaff

TBM - theater ballistic missile

TBMD- theater ballistic missile defense

TLAM - Tomahawk land attack missile

TSSE - Total Ship System Engineering

UAV - unmanned aerial vehicle

VAMOSC - visibility and management of operational and support costs

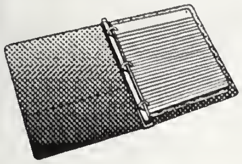
VGAS - vertical gun advanced system

VLS - vertical launch system

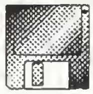
APPENDIX B. DEFINITIONS

configuration -	the model output which includes the collection of systems added to the base arsenal ship and the warship escorts required to protect the arsenal ship
leaker -	an anti-ship cruise missile that is engaged but not defeated by defensive measures [Ref. 8]
stealth -	the reduction and control of observable signatures that are exploitable by the enemy including electromagnetic emissions, radar cross section, visual (wake), infrared, acoustic, and magnetic signatures [Ref. 9]
staying power -	the number of hits that a ship can absorb before being rendered not mission capable [Ref. 8]
susceptibility -	the inability of a ship to avoid the sensors, weapons, and weapons effects of a man-made hostile environment [Ref. 11]
survivability -	the capability of a surface ship to avoid and/or withstand a man-made hostile environment while performing its mission [Ref. 11]
vulnerability -	the conditional probability of being killed given that a ship is hit [Ref. 11]

APPENDIX C. USER'S GUIDE



Arsenal Ship Tradeoff Analysis Program
User's Guide



LT Ronald Bush | LT Arthur Cimiluca

Note: This program requires Microsoft's Excel spreadsheet program for Windows.

1. **Installation**

A. Create a directory on hard drive: **C:/ arsenal**.

B. Copy all files from 3.5 inch floppy disk to **C:/ arsenal**. Your directory should contain the following files:

alcom22.exe	batsust.exe
alcom22.pas	batsust.pas
arsenal.exe	icon_h.dll
arsenal.pas	icon_y.dll
arsenal.xls	

Note: additional text files will be created in the **C:/ arsenal** directory when the program runs.

2. **Running to solve for configurations**

A. Open the file **arsenal.xls**.

B. Examine the first sheet (labeled **Arsenal**). Sample data, which represents the best unclassified information the authors could locate at the time of writing, is provided in all cells.

C. Update cost, kill probability, radar cross section, or ordnance load data if required.

D. Set the minimum and maximum ranges for each type of escort ship and candidate system. If a system or escort is not listed, add it in the appropriate section by typing the name over an **n/a** cell and entering the required characteristic data.

E. Select **No Surprise Attack** or **Surprise attack Option**.

F. Select **Degrade Stealth by 1/2...** unless detailed radar cross section data is available for all ships and systems examined.

G. Enter threat data for **Days**, **Attacks/Day**, and **Missile/Attack**.

H. Change **missile explosive weight** if considering other than Exocet equivalents.

I. Enter the **Minimum Survival Probability threshold** of interest.

J. Enter **Annual Life Cycle Cost** limit.

K. Click on **Step # 1** button for the Survivability Sub-Model (Update).

- Answer yes to the "Replace existing 'FIGURES.TXT'?" prompt.

- Answer yes to the "Replace existing 'ARSENAL.XLS'?" prompt.

L. Highlight and double click on **Step # 2** button (Enumerate).

M. Highlight and double click on **Step # 3** (Run Pgm) button.

- Note the number of configurations that meet your criteria and close the text box.

N. Click on **Step # 4** (Display) button.

- The **All Data** sheet will be displayed. It lists all the configurations that meet your input requirements. Normal spreadsheet functions, such as sorting, can be performed to organize the output data as desired.

- Also shown is a graph of survivability verses cost. This graph is useful in identifying interesting configurations that warrant closer examination. The graph's properties may require modification if the entire range of the budget is not displayed or if all points are not displayed over the entire x-axis range. To adjust the graph, first double click on it.

(1) Then to modify the number of data points, double click on the plotted curve. Select **Names and Values**, and observe the **Y-Values** line. The last number after the "$" represents the number of data points; overwrite it with the number of configurations that met your criteria (from step 2.M). Then select the **X- Values** tab, overwrite the last number after the "$" on the **X-Values** line as above, and click on the **OK** button to exit Format Data Series.

(2) To change the cost scale, double click on the cost values and change the maximum, minimum, and increment values as desired. After changes are made click on the **OK** button.

3. Displaying Configurations

Up to six configurations can be displayed in a graphical representation of cost, survivability, and individual systems and ships in the **All Data** sheet. There are two options for displaying results.

- Option 1: The user may sort the data using the spreadsheet function in Excel and display the top six results by pressing the 'Display first 6 results' button.

- Option 2: The user may determine which configurations to display from either the graph or the spreadsheet data. Select a configuration by highlighting its entire row and copying it into the **Details** sheet. Copy the first configuration into line 3 of the **Details** sheet and subsequent configurations into lines 10,17,24,31, and 38. Scroll down the **Details** sheet to see the composite graph.

This graph may be tailored to the user's needs. Adjustments to the cost scale (left) or survivability scale (right) can be made by double clicking on the desired axis or axes and changing the scale as in step 2.N.(2) above.

4. Printing Graphs

The options are numerous; three ways are described below.

A. Select *Print*; then *Print Selected Sheet*.

B. Activate a graph by double clicking on it. Select *Print*; then *Print Selected Chart.* This method prints the graph on an entire sheet of paper and affords the user some formatting options.

C. Highlight a graph by clicking on it. Then *copy* it to the windows clipboard and *paste* it into a compatible program which can be printed.

Note: Perhaps the best way to import a graph to another program is by using the *Paste Special* under the *Edit* menu and selecting *Paste as Picture*.

5. Running to solve for Sustainability

The same procedures apply as for "Running to solve for configuration." The step number

and difference are given below.

2.D. Hardwire the desired escorts and candidate systems by setting **Min Qty** and **Max Qty** the same.

2.G. Not required. Sustainability program will solve for number of missiles.

2.I. Note: Min Survivability threshold is for the Arsenal Ship, not for the escorts. Each escort will fight until OOA, while the Arsenal Ship will fight until it falls below the threshold.

2.N. There is no Step #4 button

3. To display data use Notepad or any other text compatible viewer and open the file c:\arsenal\history.txt.

APPENDIX D. ARSENAL SHIP TRADEOFF ANALYSIS PROGRAM

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